

# WINP2015

Workshop on  
the Intermediate  
Neutrino Program

Hosted at Brookhaven National Laboratory  
February 4-6, 2015

nu interactions Session

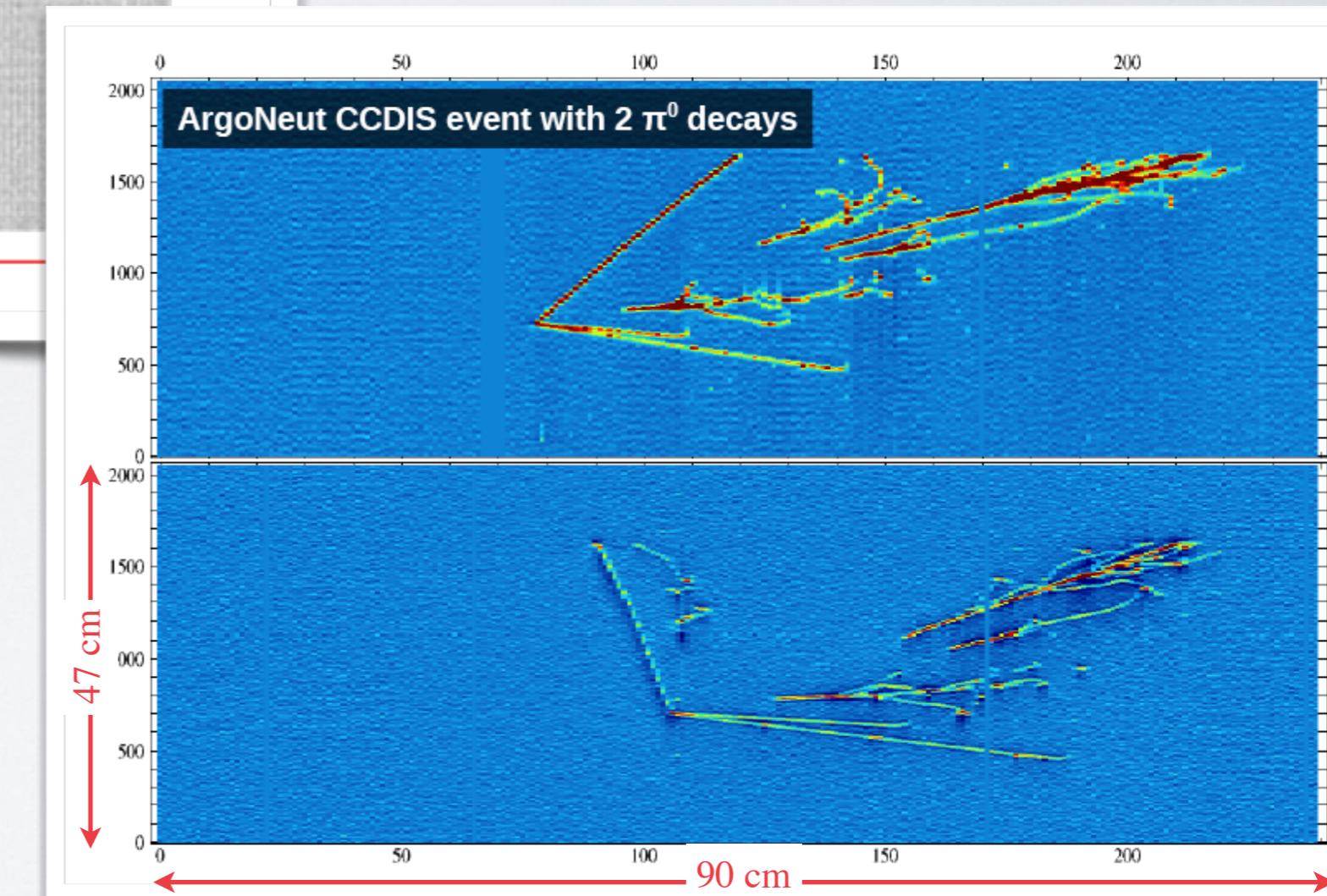
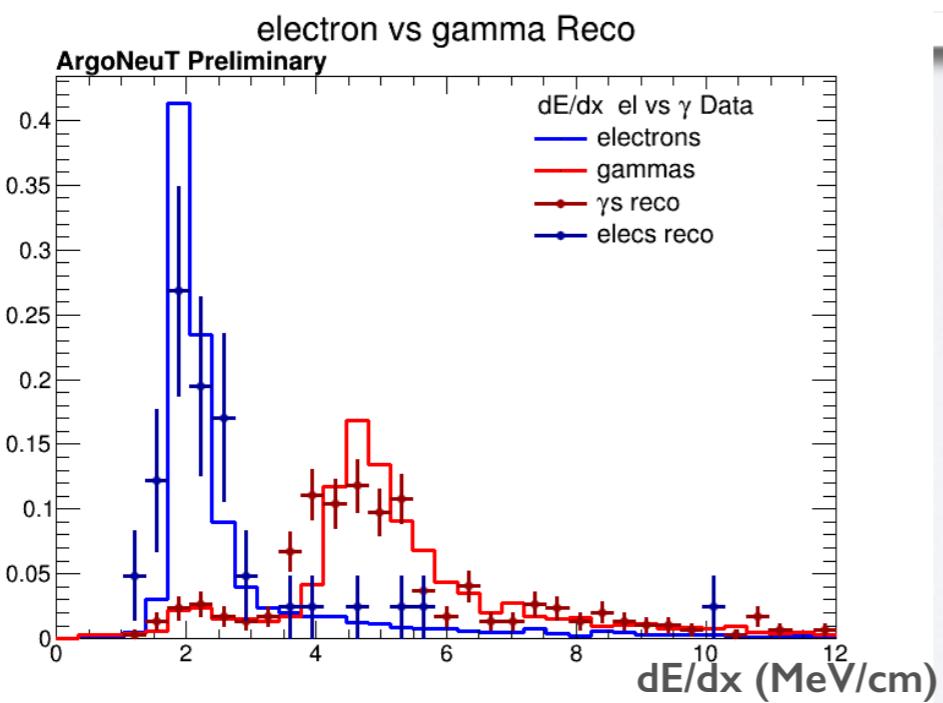
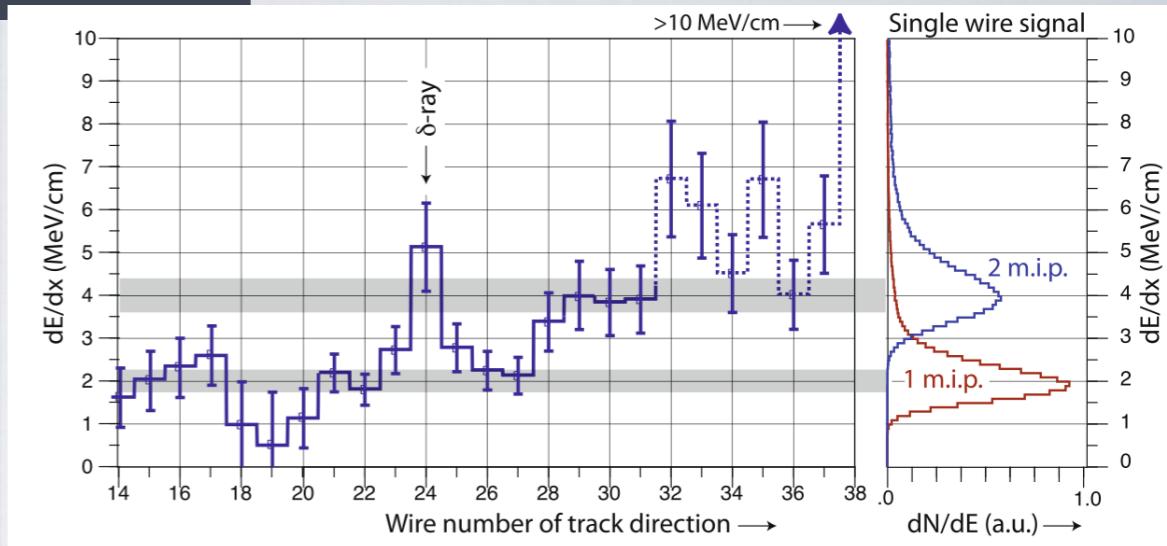
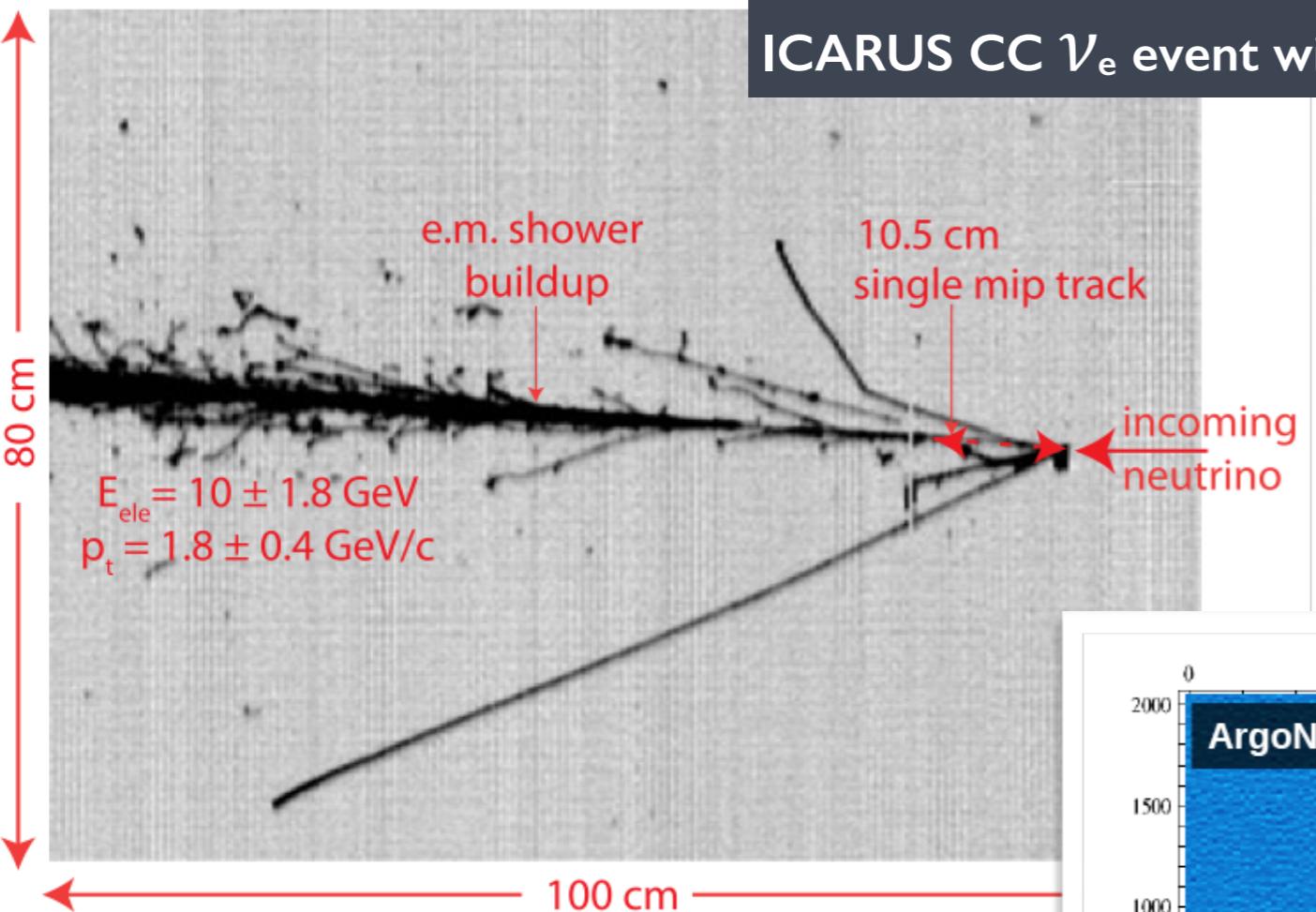
## FUTURE LAR NEUTRINO INTERACTION PROGRAM

BNL  
Feb. 5, 2015

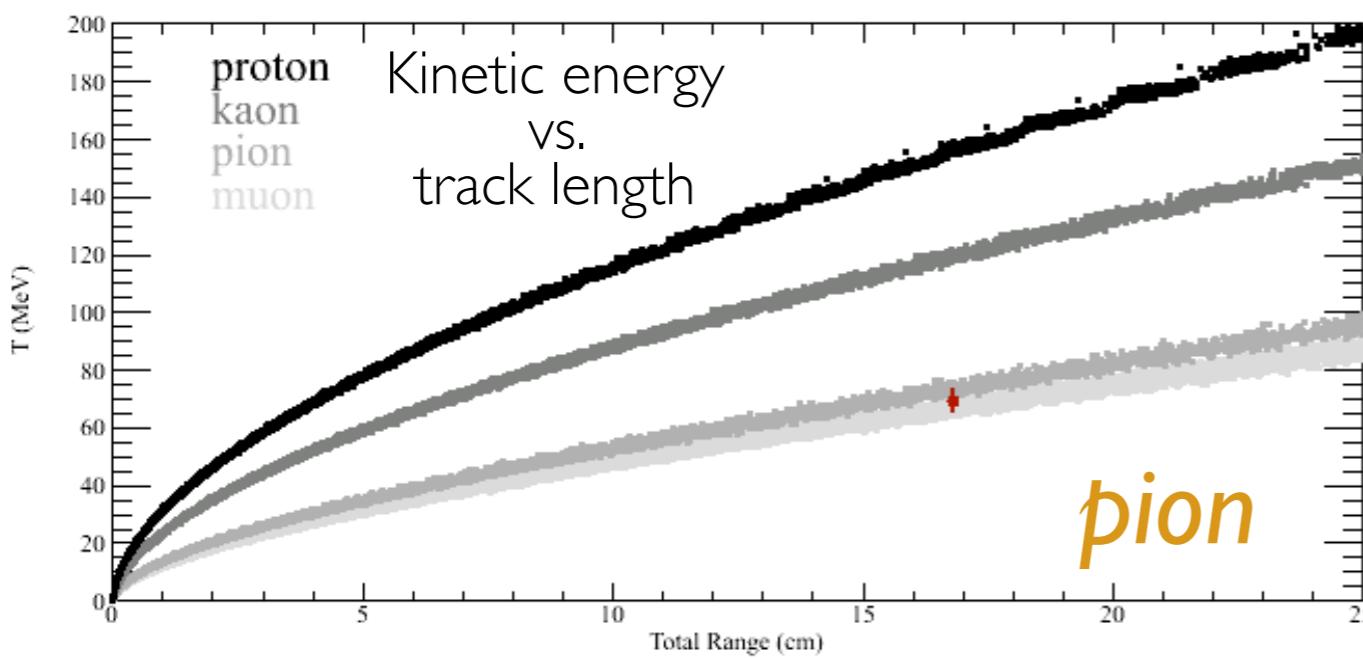
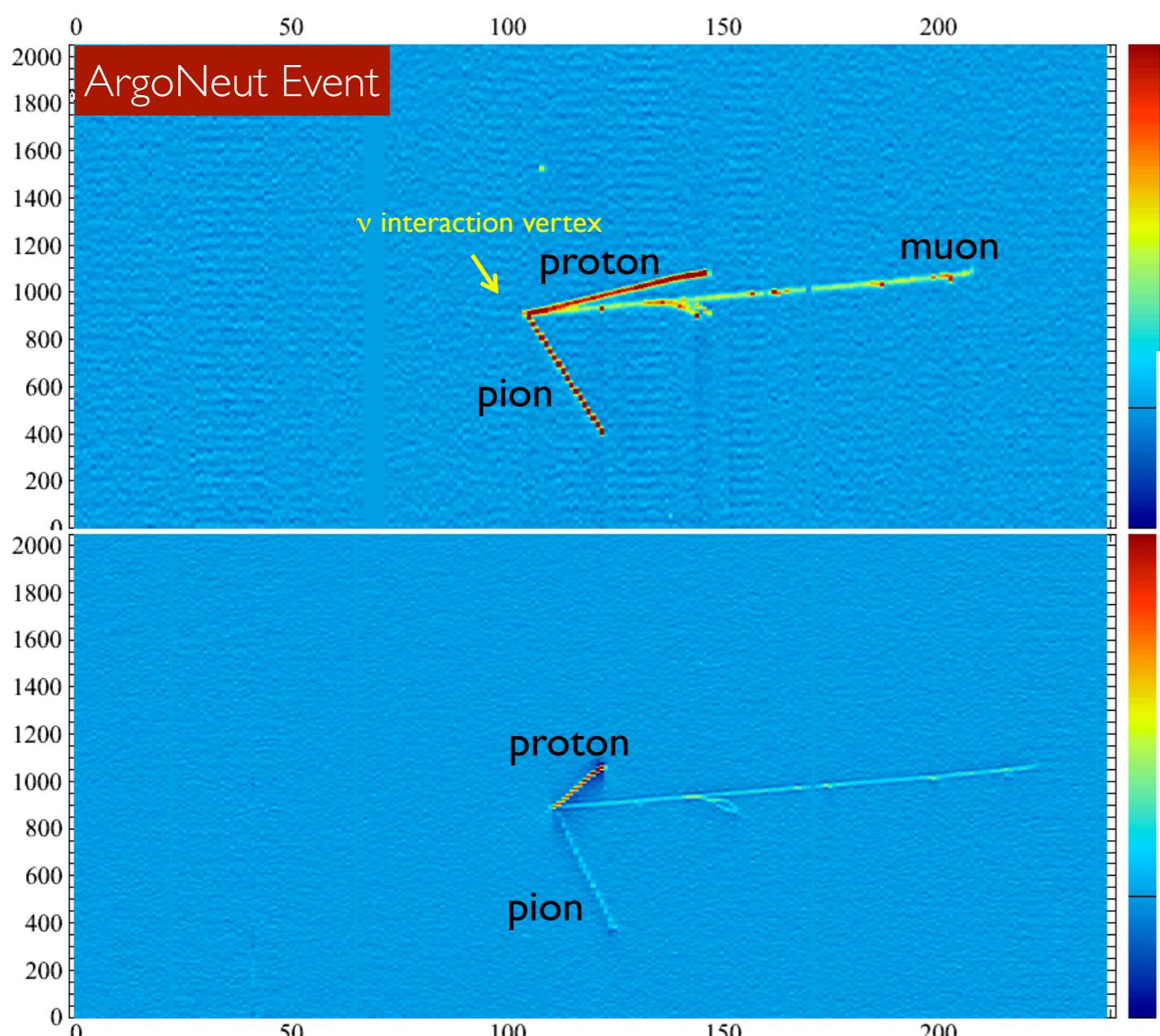
FLAVIO CAVANNA\*  
FERMILAB, NEUTRINO DIVISION

\* on leave: University of L'Aquila (Italy)

## ICARUS CC $\nu_e$ event with electron

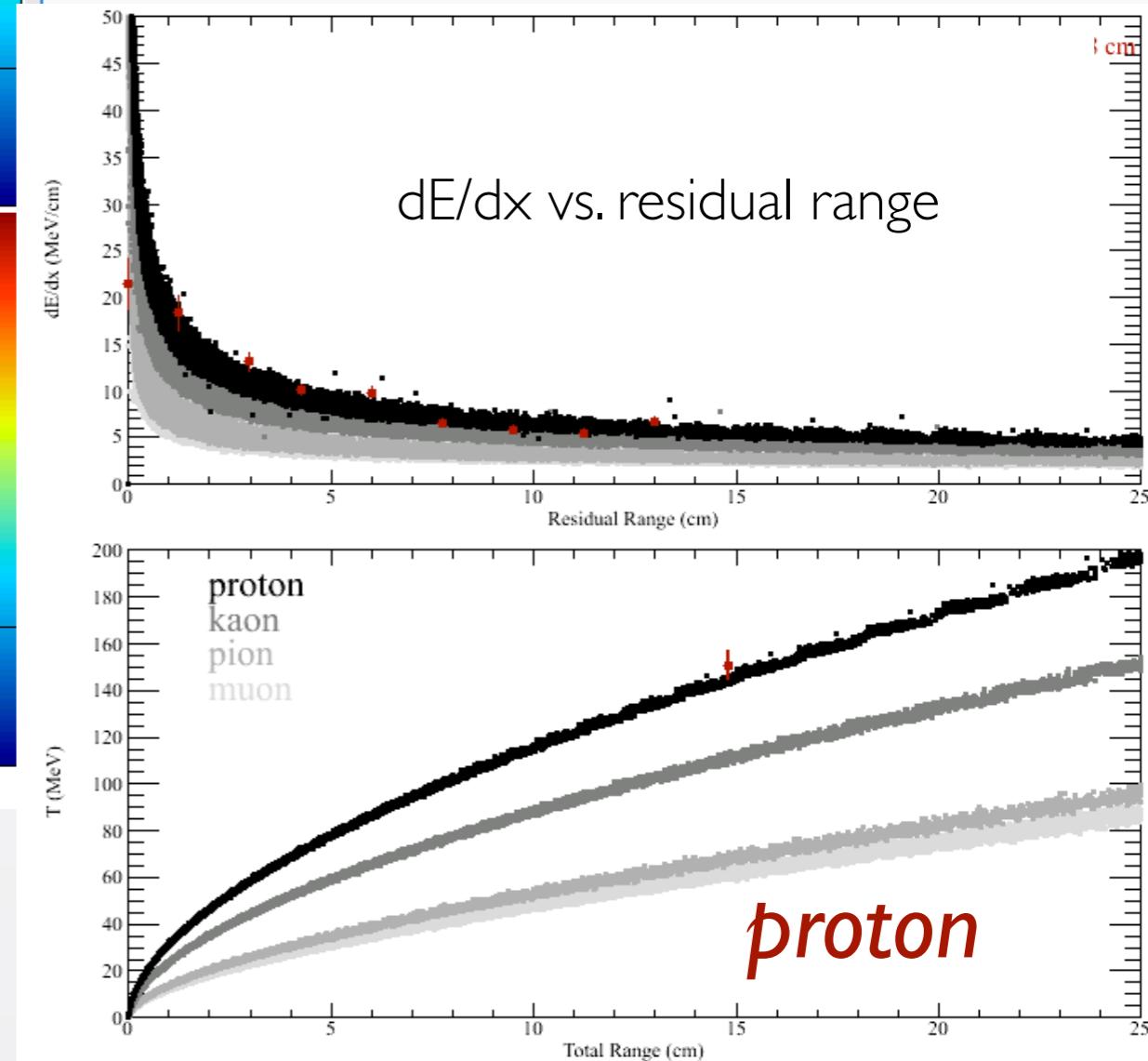


$\nu_e$  appearance **background rejection**  
 $\pi^0 \rightarrow$  photon / electron discrimination



# $p/\pi^\pm$ identification

Exclusive topologies reconstruction

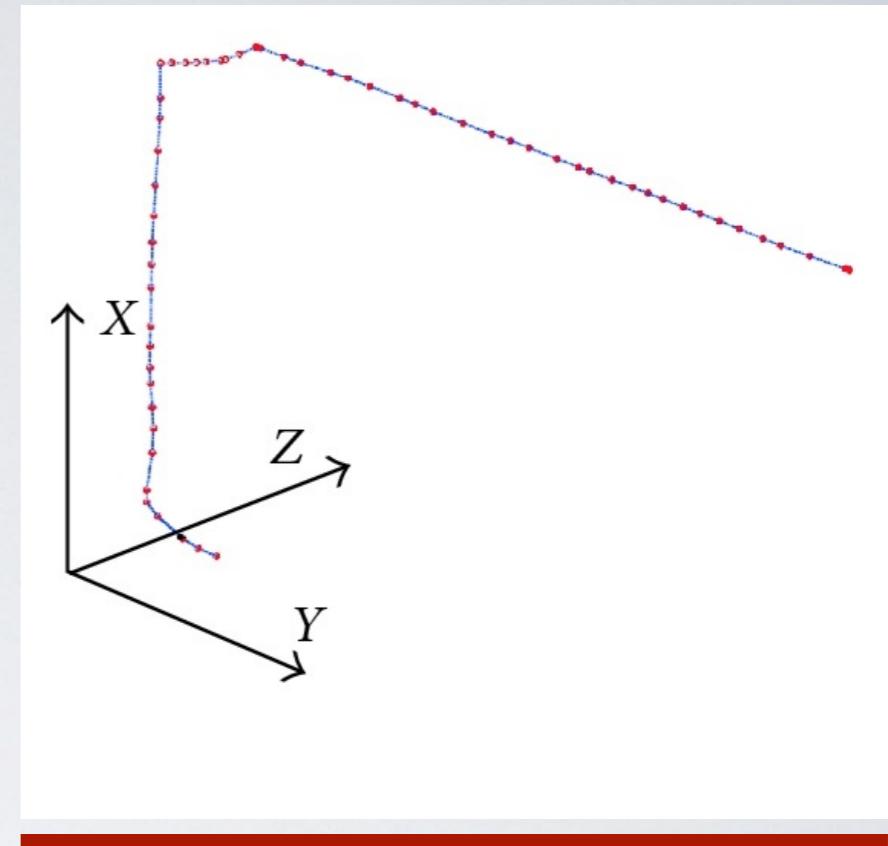
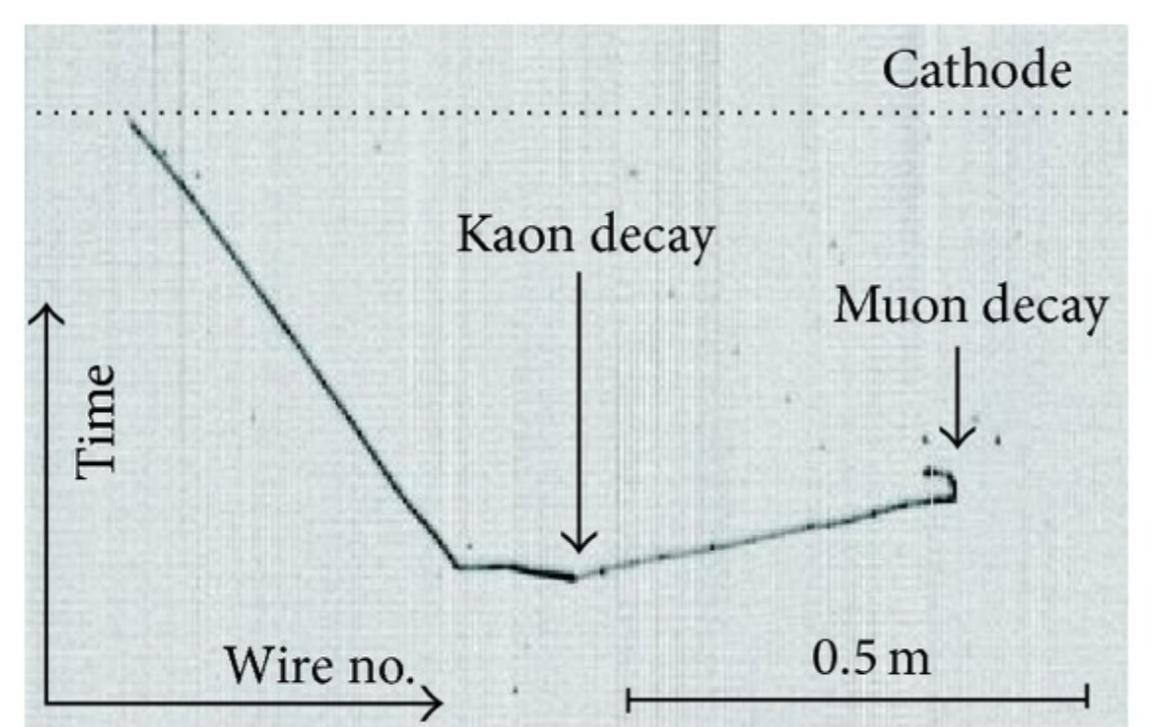
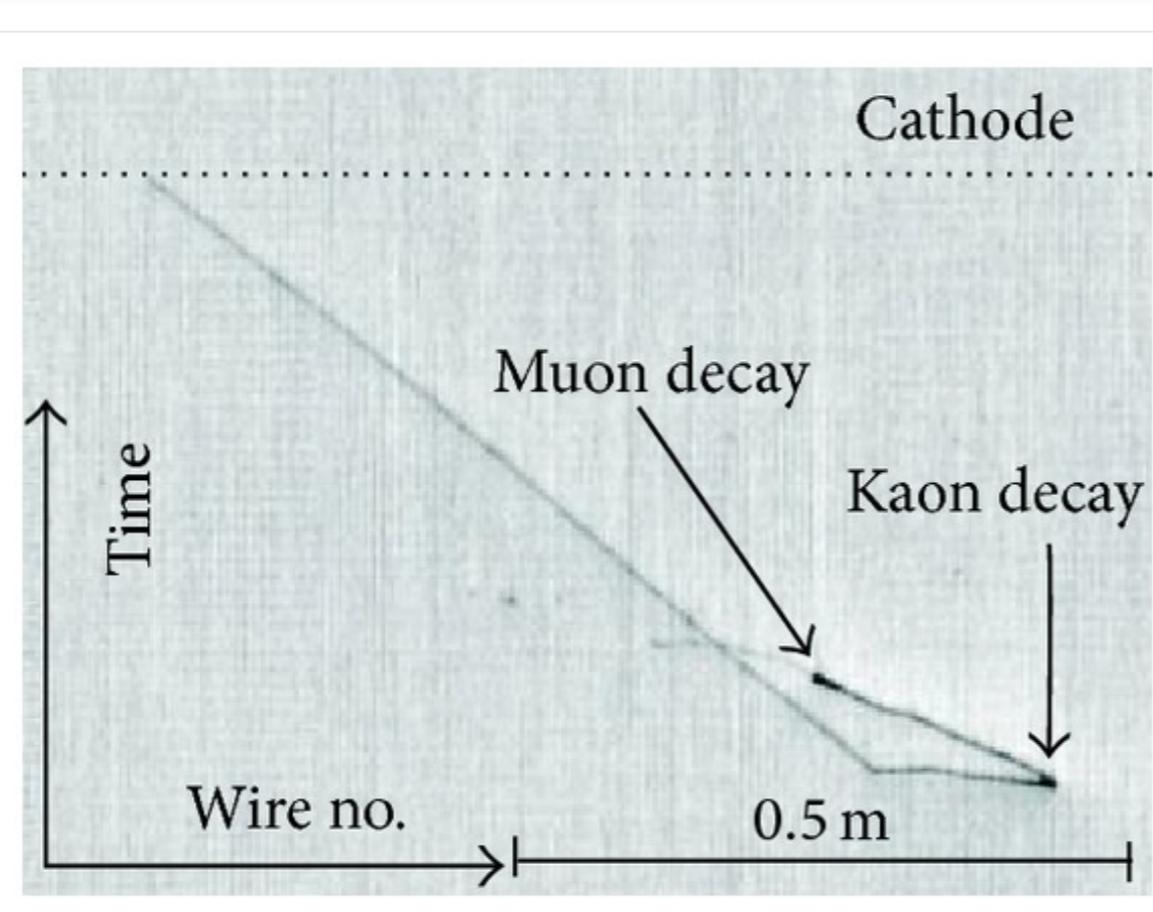


ArgoNeuT pion reconstruction threshold:  
~8 MeV Kinetic energy

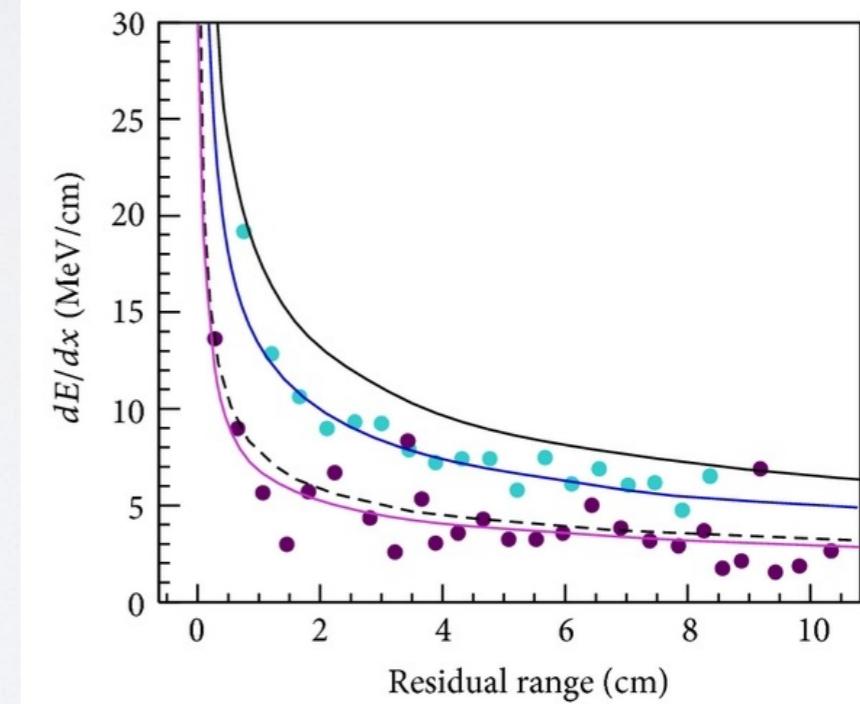
proton reconstruction threshold:  
~20 MeV Kinetic energy

# Kaon Identification

ICARUS Event

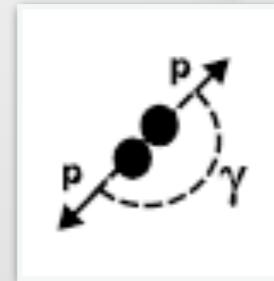
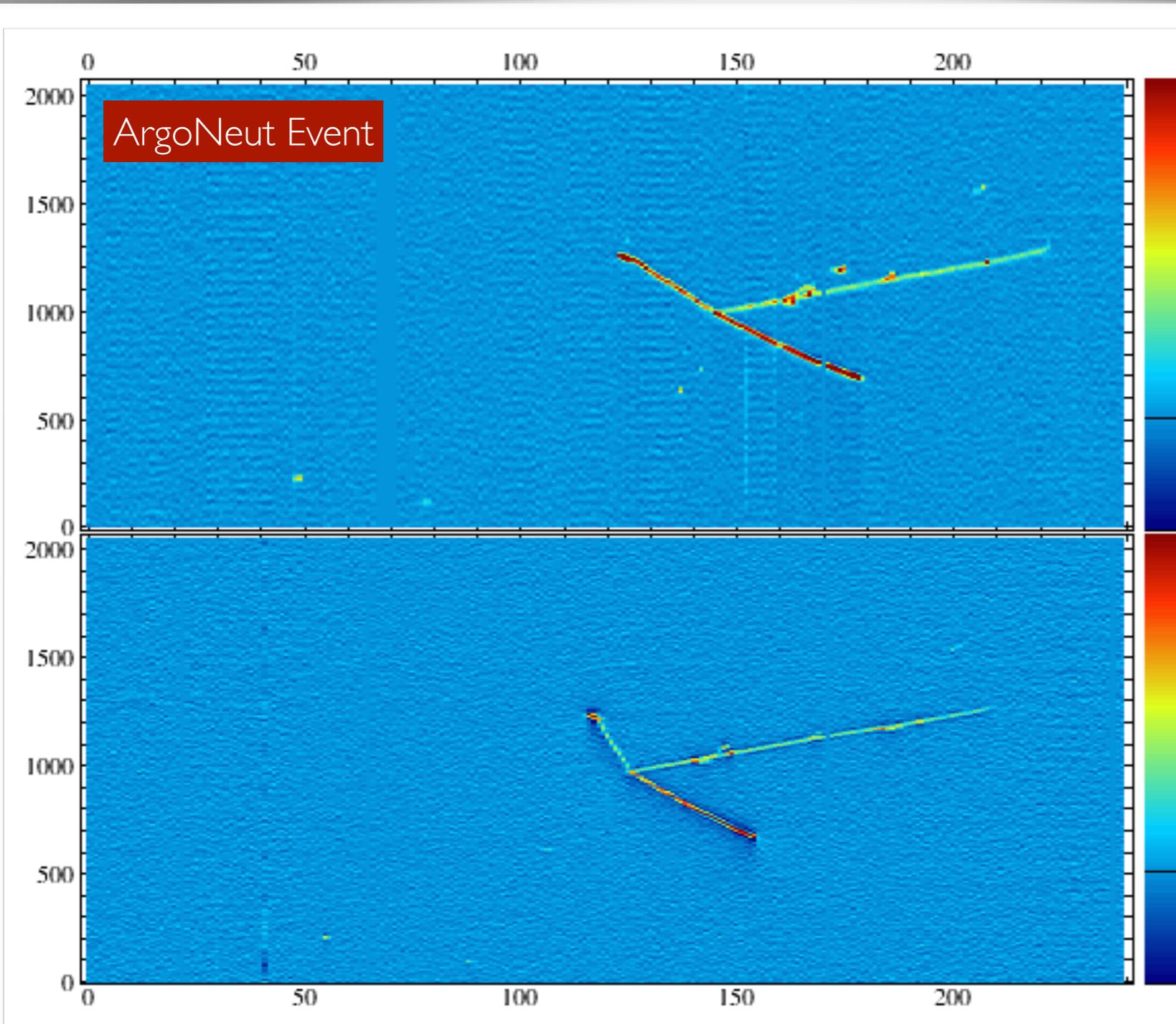


Rare topologies reconstruction



# Sensitivity to Nuclear Effects in Neutrino Interactions

$(\mu^- + 2p)$  data sample - “*Hammer Events*”



$$\cos(\gamma) < -0.95$$

Visually the signature of these events gives the appearance of a hammer, with the muon forming the handle and the back-to-back protons forming the head.

New perspectives are now open for a detailed reconstruction of the complex event topologies emerging in final state from neutrino-nucleus interactions.

LAr-TPC detectors provide full 3D imaging combined with efficient particle identification capability and precise calorimetric energy reconstruction allowing for **exclusive topologies recognition and direct exploration of nuclear effects** with superior sensitivity.

Instead of MC based classification of the event rates in terms of interaction channel (QE, RES, DIS, etc), neutrino events in LAr can be (are) directly categorized in terms of **final state topology** based on particle multiplicity:

“0-pion” (i.e.  $\ell^\pm + N\mathbf{p}$ , where  $N=0,1,2\dots$ ),

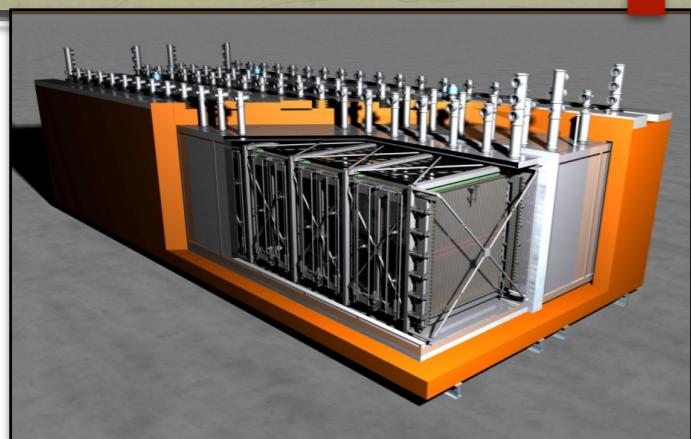
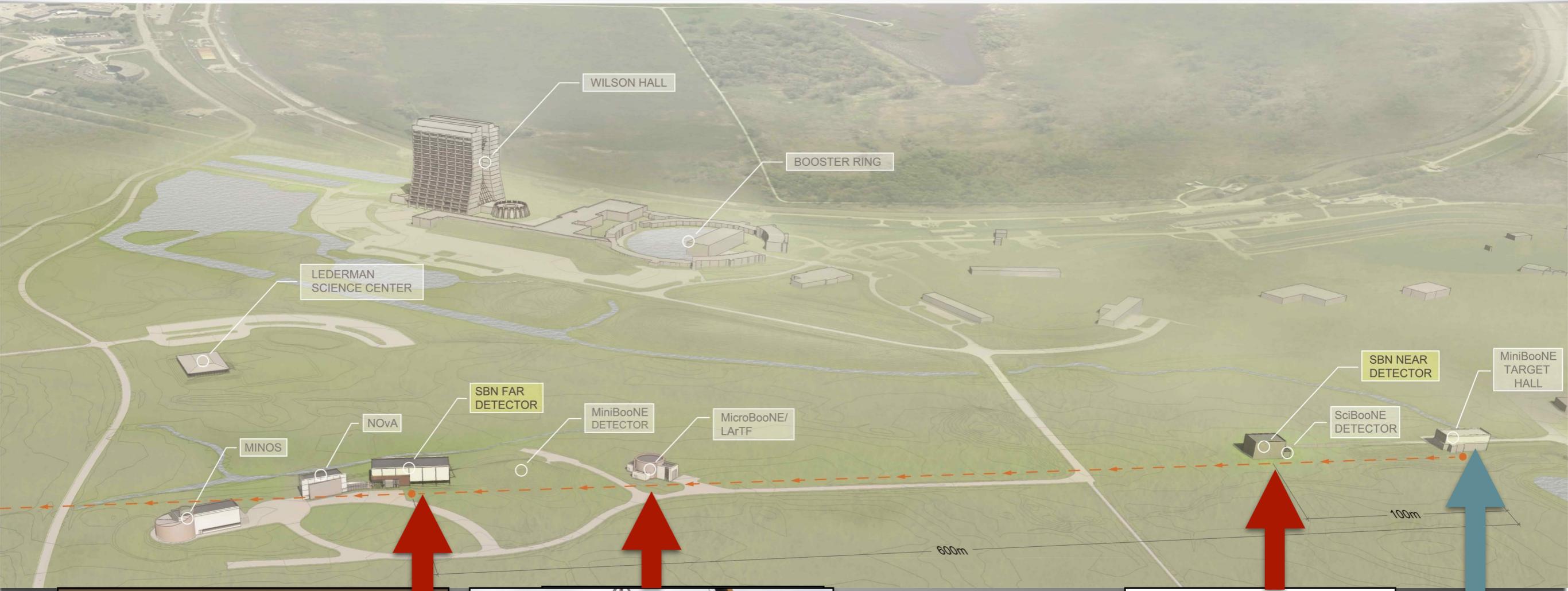
“1-pion” (i.e.  $\ell^\pm + 1\pi + N\mathbf{p}$ , where  $N=0,1,2\dots$ ),

etc..

In **exclusive topology cross-section determination, the use of MC information is limited to the estimate of the event selection efficiency and acceptance**

**ULTIMATELY, THIS APPROACH WILL ALSO ALLOW FOR MOST PRECISE RECONSTRUCTION OF THE INCOMING NEUTRINO ENERGY FROM THE LEPTON AND PROTON(S) (AND PION) RECONSTRUCTED KINEMATICS.**

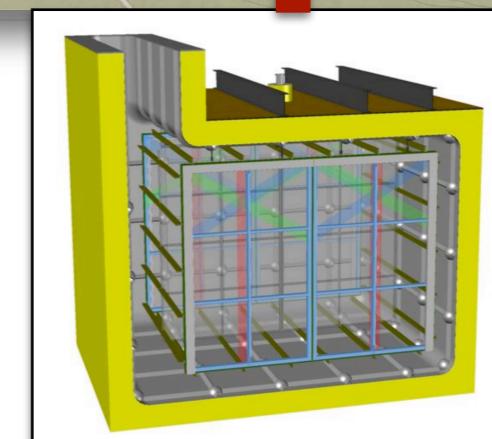
# the Fermilab Booster Neutrino Beam



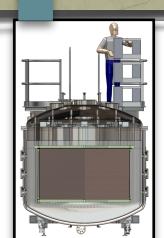
Icarus-T600



MicroBooNE



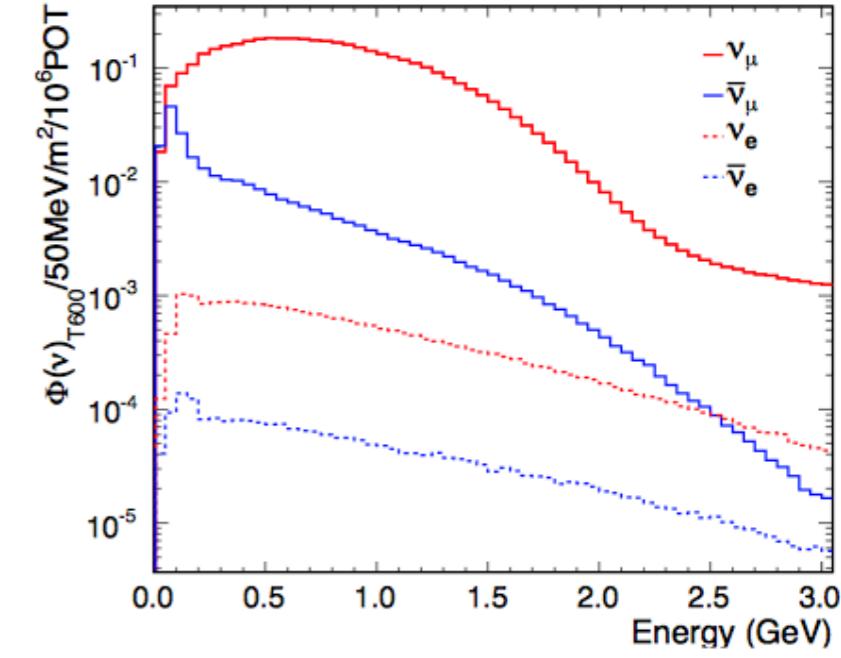
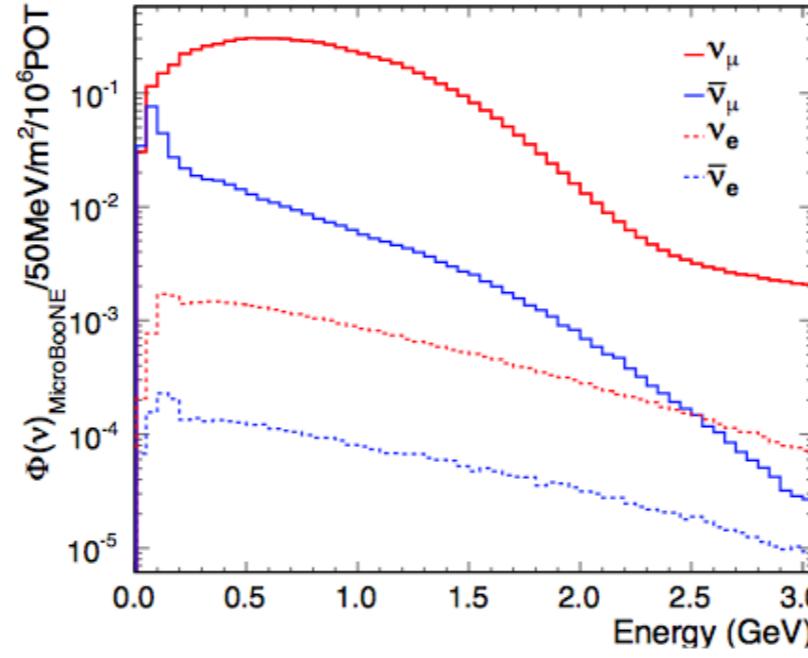
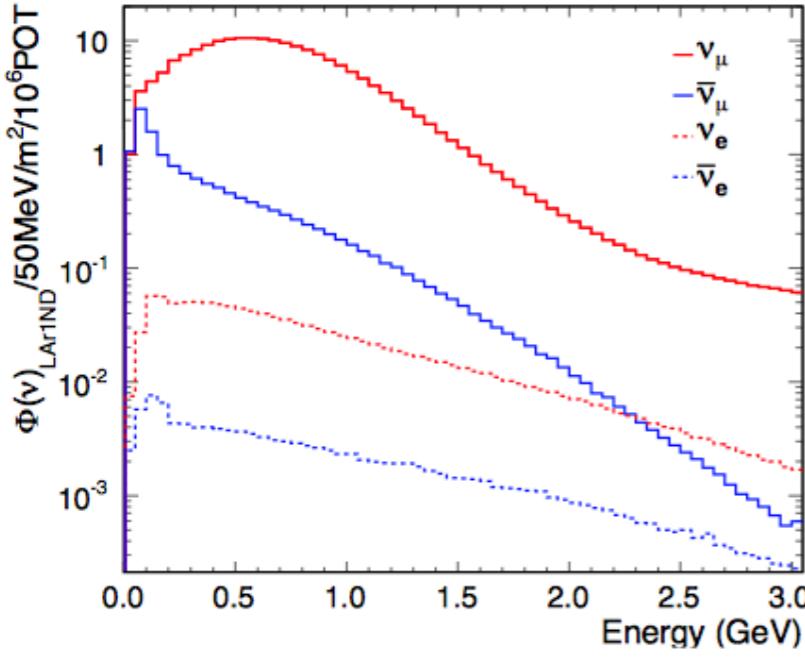
LArI-ND



Captain

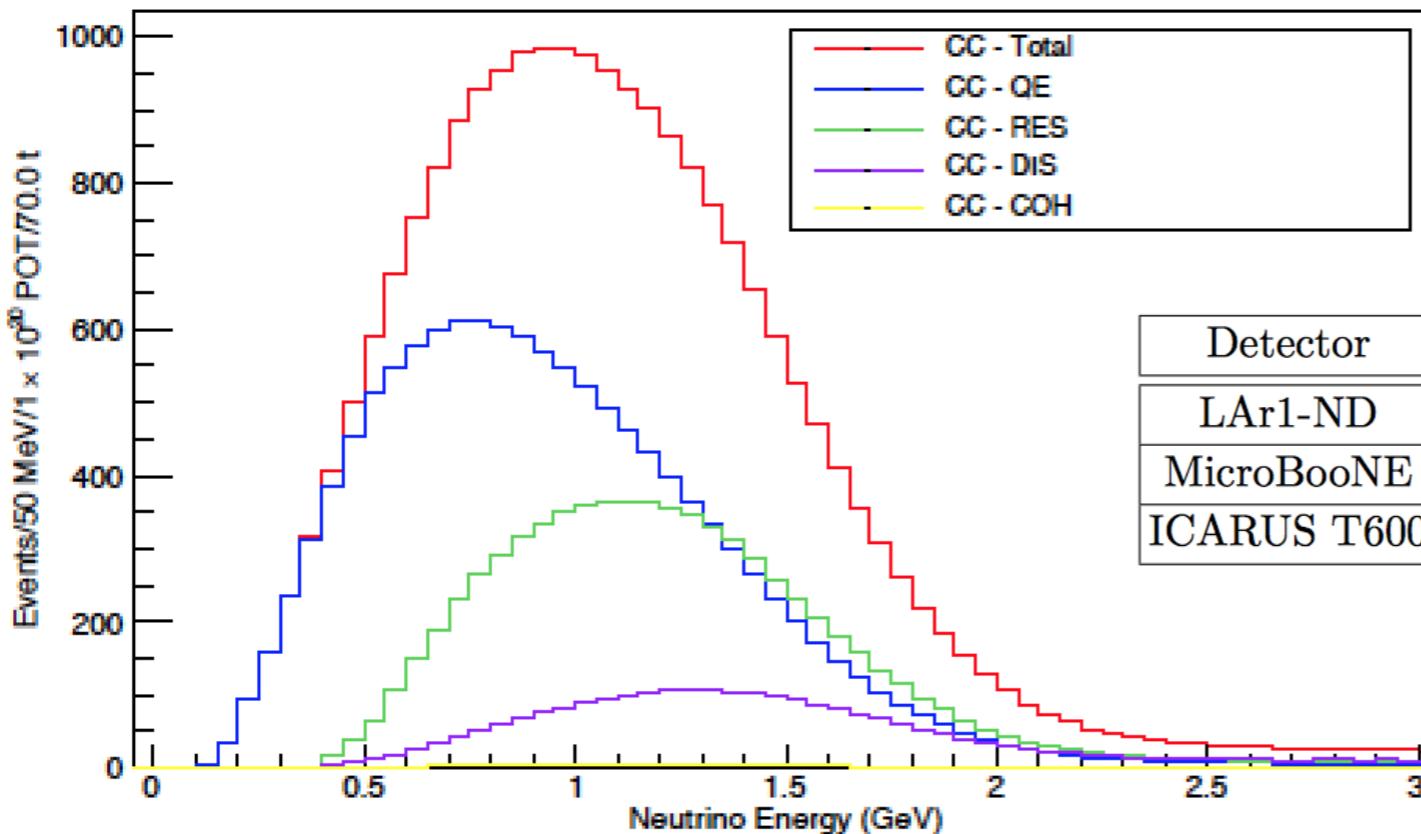
A LArTPC  
for  
SN Xsect

A Three LArTPC Detector  
Short-Baseline Neutrino Oscillation Program



*The Booster Neutrino Beam flux at the three SBN detectors: (left) LAr1-ND, (center) MicroBooNE, and (right) ICARUS T600.*

### $\nu_\mu$ Events as a Function of Neutrino Energy



### Booster Neutrino Beam

| Detector    | Distance from BNB Target | LAr Total Mass | LAr Active Mass |
|-------------|--------------------------|----------------|-----------------|
| LAr1-ND     | 110 m                    | 220 t          | 112 t           |
| MicroBooNE  | 470 m                    | 170 t          | 89 t            |
| ICARUS T600 | 600 m                    | 760 t          | 476 t           |

| Process                            |   | No. Events | in active volume (89 t) |
|------------------------------------|---|------------|-------------------------|
|                                    | $\nu_\mu$ Events (By Final State Topology)                    |            |                         |
| CC Inclusive                       |   | 122,100    | 178,100                 |
| CC 0 $\pi$                         | $\nu_\mu N \rightarrow \mu + Np$                              | 78,500     |                         |
|                                    | · $\nu_\mu N \rightarrow \mu + 0p$                            | 16,500     |                         |
|                                    | · $\nu_\mu N \rightarrow \mu + 1p$                            | 44,200     |                         |
|                                    | · $\nu_\mu N \rightarrow \mu + 2p$                            | 8,300      |                         |
|                                    | · $\nu_\mu N \rightarrow \mu + \geq 3p$                       | 9,500      |                         |
| CC 1 $\pi^\pm$                     | $\nu_\mu N \rightarrow \mu + \text{nucleons} + 1\pi^\pm$      | 30,300     |                         |
| CC $\geq 2\pi^\pm$                 | $\nu_\mu N \rightarrow \mu + \text{nucleons} + \geq 2\pi^\pm$ | 2,700      |                         |
| CC $\geq 1\pi^0$                   | $\nu_\mu N \rightarrow \mu + \text{nucleons} + \geq 1\pi^0$   | 13,400     |                         |
| NC Inclusive                       |   | 45,900     | 67,000                  |
| NC 0 $\pi$                         | $\nu_\mu N \rightarrow \text{nucleons}$                       | 29,900     |                         |
| NC 1 $\pi^\pm$                     | $\nu_\mu N \rightarrow \text{nucleons} + 1\pi^\pm$            | 6,900      |                         |
| NC $\geq 2\pi^\pm$                 | $\nu_\mu N \rightarrow \text{nucleons} + \geq 2\pi^\pm$       | 900        |                         |
| NC $\geq 1\pi^0$                   | $\nu_\mu N \rightarrow \text{nucleons} + \geq 1\pi^0$         | 9,200      |                         |
|                                    | $\nu_e$ Events  |            |                         |
| CC Inclusive                       |   | 820        | 1,200                   |
| NC Inclusive                       |   | 290        |                         |
| Total $\nu_\mu$ and $\nu_e$ Events |   | 169,180    | 246,000                 |
|                                    | $\nu_\mu$ Events (By Physical Process )                       |            |                         |
| CC QE                              | $\nu_\mu n \rightarrow \mu^- p$                               | 67,500     |                         |
| CC RES                             | $\nu_\mu N \rightarrow \mu^- \pi N$                           | 37,300     |                         |
| CC DIS                             | $\nu_\mu N \rightarrow \mu^- X$                               | 14,500     |                         |
| CC Coherent                        | $\nu_\mu Ar \rightarrow \mu Ar + \pi$                         | 480        |                         |

Table 1: Estimated event rates using GENIE (v2.8) in a 6.6e20 POT exposure of MicroBooNE, located 470m from the neutrino source, the Booster Neutrino Beam. In enumerating proton multiplicity, we assume a kinetic energy threshold on protons of 20 MeV. The  $0\pi$  topologies include any number of neutrons in the event. This study uses a 17cm fiducial volume cut in MicroBooNE, which gives a fiducial volume of 61t.

| Process                                    |   | No. Events | Events/ton | Stat. Uncert. |
|--|---|------------|------------|---------------|
| $\nu_\mu$ Events (By Final State Topology) |   |            |            |               |
| CC Inclusive                               |   | 5,212,690  | 46,542     | 0.04%         |
| CC 0 $\pi$                                 | $\nu_\mu N \rightarrow \mu + Np$                              | 3,551,830  | 31,713     | 0.05%         |
|  | · $\nu_\mu N \rightarrow \mu + 0p$                            | 793,153    | 7,082      | 0.11%         |
|  | · $\nu_\mu N \rightarrow \mu + 1p$                            | 2,027,830  | 18,106     | 0.07%         |
|  | · $\nu_\mu N \rightarrow \mu + 2p$                            | 359,496    | 3,210      | 0.17%         |
|  | · $\nu_\mu N \rightarrow \mu + \geq 3p$                       | 371,347    | 3,316      | 0.16%         |
| CC 1 $\pi^\pm$                             | $\nu_\mu N \rightarrow \mu + \text{nucleons} + 1\pi^\pm$      | 1,161,610  | 10,372     | 0.09%         |
| CC $\geq 2\pi^\pm$                         | $\nu_\mu N \rightarrow \mu + \text{nucleons} + \geq 2\pi^\pm$ | 97,929     | 874        | 0.32%         |
| CC $\geq 1\pi^0$                           | $\nu_\mu N \rightarrow \mu + \text{nucleons} + \geq 1\pi^0$   | 497,963    | 4,446      | 0.14%         |
| NC Inclusive                               |   | 1,988,110  | 17,751     | 0.07%         |
| NC 0 $\pi$                                 | $\nu_\mu N \rightarrow \text{nucleons}$                       | 1,371,070  | 12,242     | 0.09%         |
| NC 1 $\pi^\pm$                             | $\nu_\mu N \rightarrow \text{nucleons} + 1\pi^\pm$            | 260,924    | 2,330      | 0.20%         |
| NC $\geq 2\pi^\pm$                         | $\nu_\mu N \rightarrow \text{nucleons} + \geq 2\pi^\pm$       | 31,940     | 285        | 0.56%         |
| NC $\geq 1\pi^0$                           | $\nu_\mu N \rightarrow \text{nucleons} + \geq 1\pi^0$         | 358,443    | 3,200      | 0.17%         |
| $\nu_e$ Events                             |   |            |            |               |
| CC Inclusive                               |   | 36798      | 329        | 0.52%         |
| NC Inclusive                               |   | 14351      | 128        | 0.83%         |
| Total $\nu_\mu$ and $\nu_e$ Events         |   | 7,251,948  | 64,750     |               |
| $\nu_\mu$ Events (By Physical Process)     |   |            |            |               |
| CC QE                                      | $\nu_\mu n \rightarrow \mu^- p$                               | 3,122,600  | 27,880     |               |
| CC RES                                     | $\nu_\mu N \rightarrow \mu^- \pi N$                           | 1,450,410  | 12,950     |               |
| CC DIS                                     | $\nu_\mu N \rightarrow \mu^- X$                               | 542,516    | 4,844      |               |
| CC Coherent                                | $\nu_\mu Ar \rightarrow \mu Ar + \pi$                         | 18,881     | 169        |               |

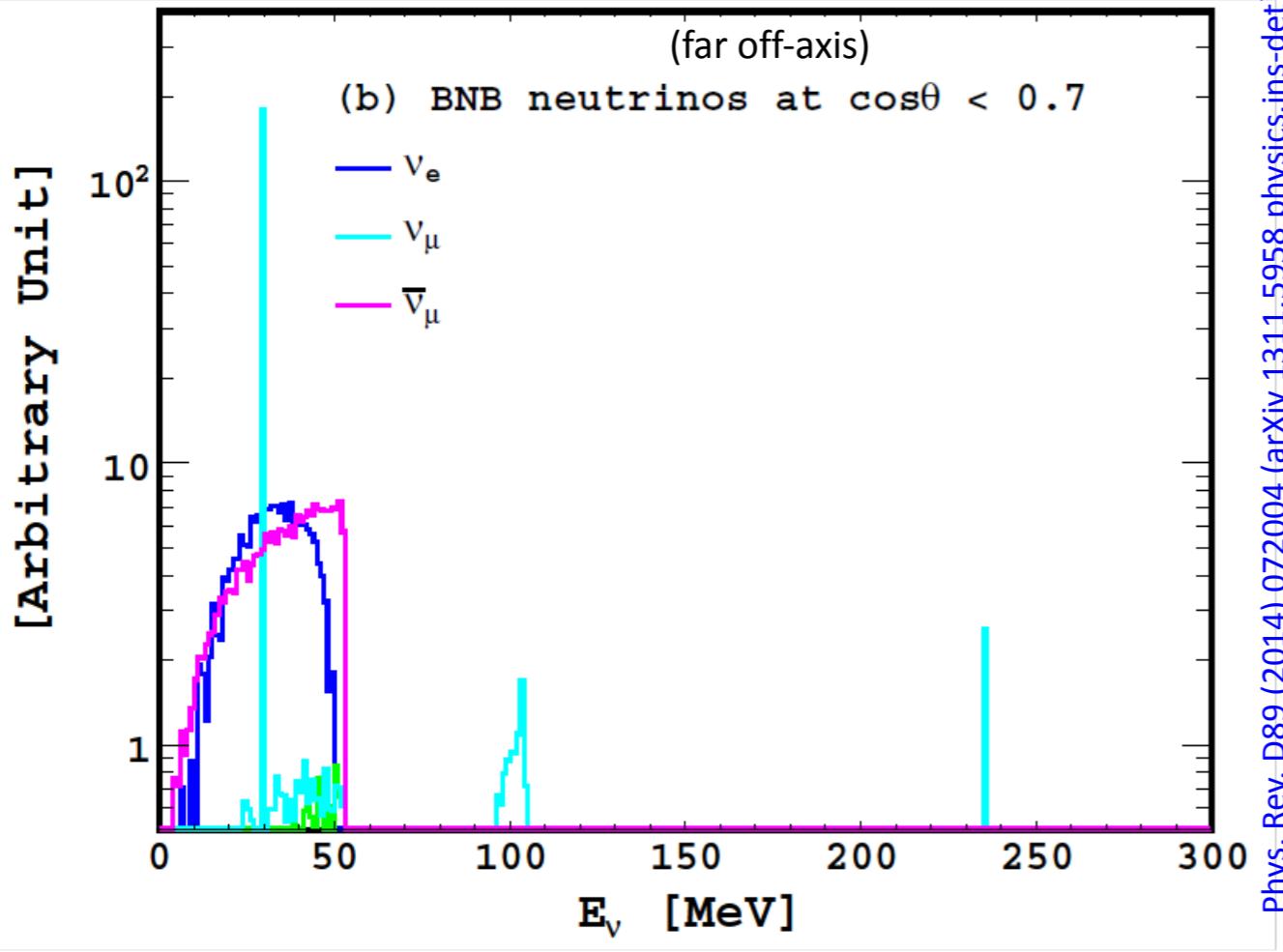
**TABLE I:** Estimated event rates using GENIE (v2.8) in the LAr1-ND active volume (112 t) for a  $6.6 \times 10^{20}$  exposure. In enumerating proton multiplicity, we assume an energy threshold on proton kinetic energy of 21 MeV. The 0 $\pi$  topologies include any number of neutrons in the event.

# ICARUS-T600 Expected Rates @ BNB

| Process                            | No. Events                                 |
|------------------------------------|--|
| CC Inclusive                       | $\nu_\mu$ Events (By Final State Topology) |
| NC Inclusive                       | 210,000                                    |
| <hr/>                              |  |
|                                    | $\nu_e$ Events                             |
| CC Inclusive                       | 2,000                                      |
| NC Inclusive                       | 780  |
| Total $\nu_\mu$ and $\nu_e$ Events | 760,000                                    |

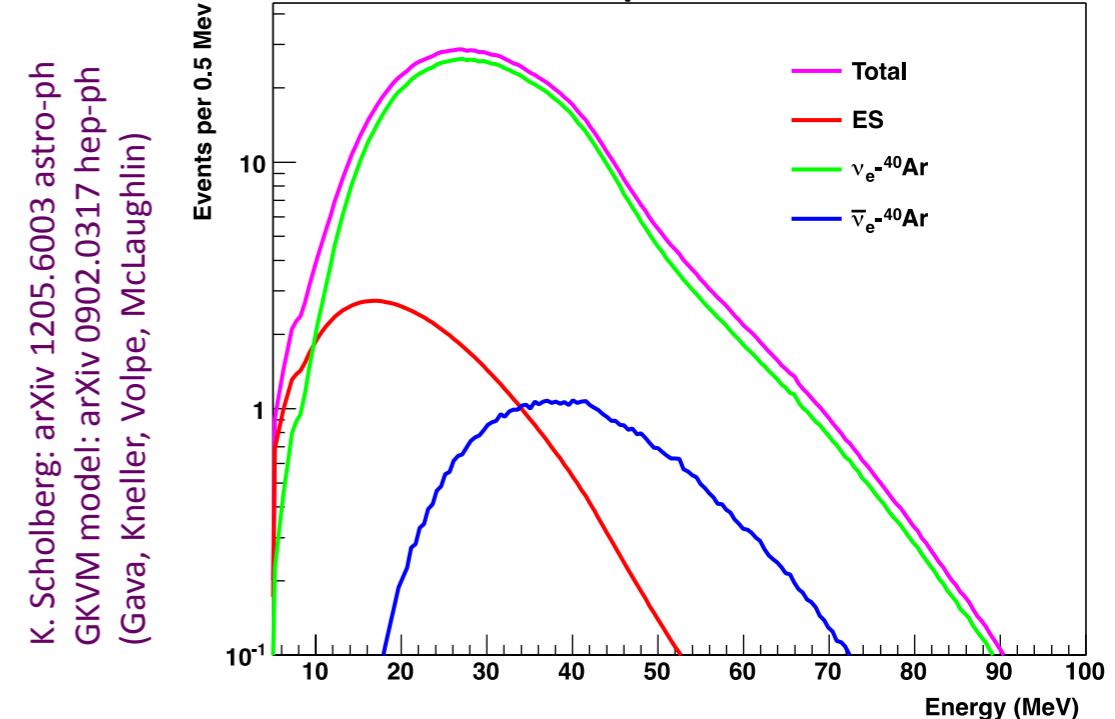
~~6.6E20 pot (2.2E20pot/yr X 3 yr)~~  
~~in detector~~  
~~Active Volume (476 t)~~

# CAPTAIN-BNB

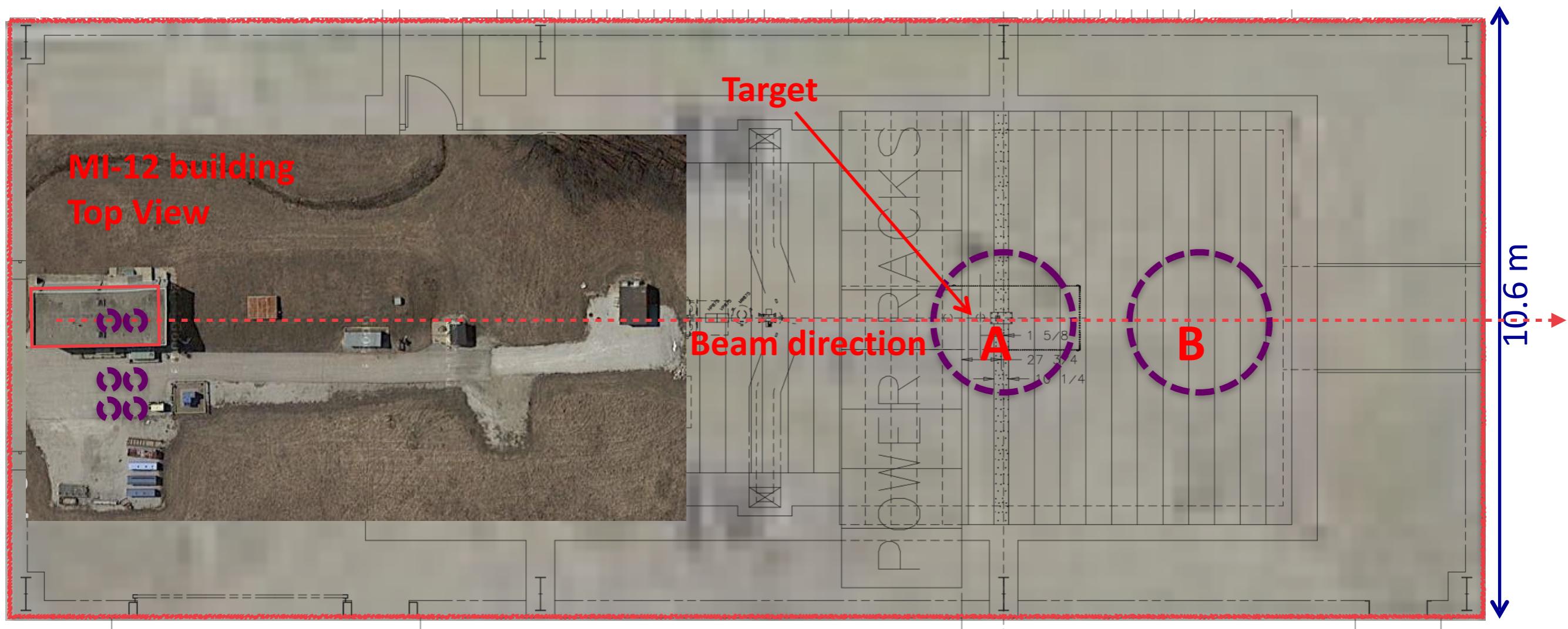


- Goal: Study neutrino-argon interactions in the energy range relevant for supernova detection
  - Xsecs have never been measured and have large theoretical uncertainties
- The flux: Neutrinos from pion decay-at-rest in an off-axis location near the Booster Neutrino Beam (BNB) target hall (MI-12)
- Measure the neutrino-argon xsec (mainly  $v_e$ ) to about 10% for neutrino energies of  $O(10)$  MeV
  - Need  $4e20$  POT for a 10% measurement
  - Less exposure required if some amount of beam off-target running is possible

- Test the ability of detecting SNe with LAr detectors (triggering, timing)
- Potentially influence the ELBNF design (e.g., photodetection devices)
- Neutron background at this location will be studied soon (SciBath)



# CAPTAIN-BNB



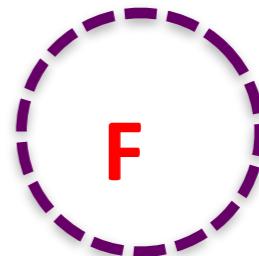
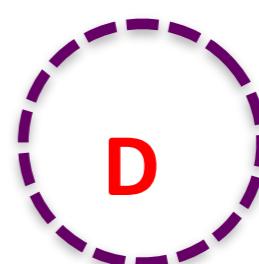
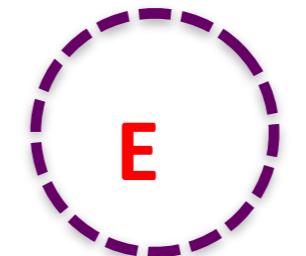
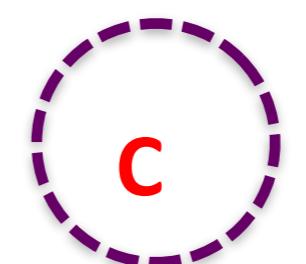
Alignment w. target & collimator

| x (m) | d (m) | Nevt (CC) | Nevt (CC) |
|-------|-------|-----------|-----------|
| 0     | 8.4   | A 354     | B 375     |
| 7.3   | 11.1  | C 217     | D 229     |
| 11.3  | 14.1  | E 145     | F 152     |

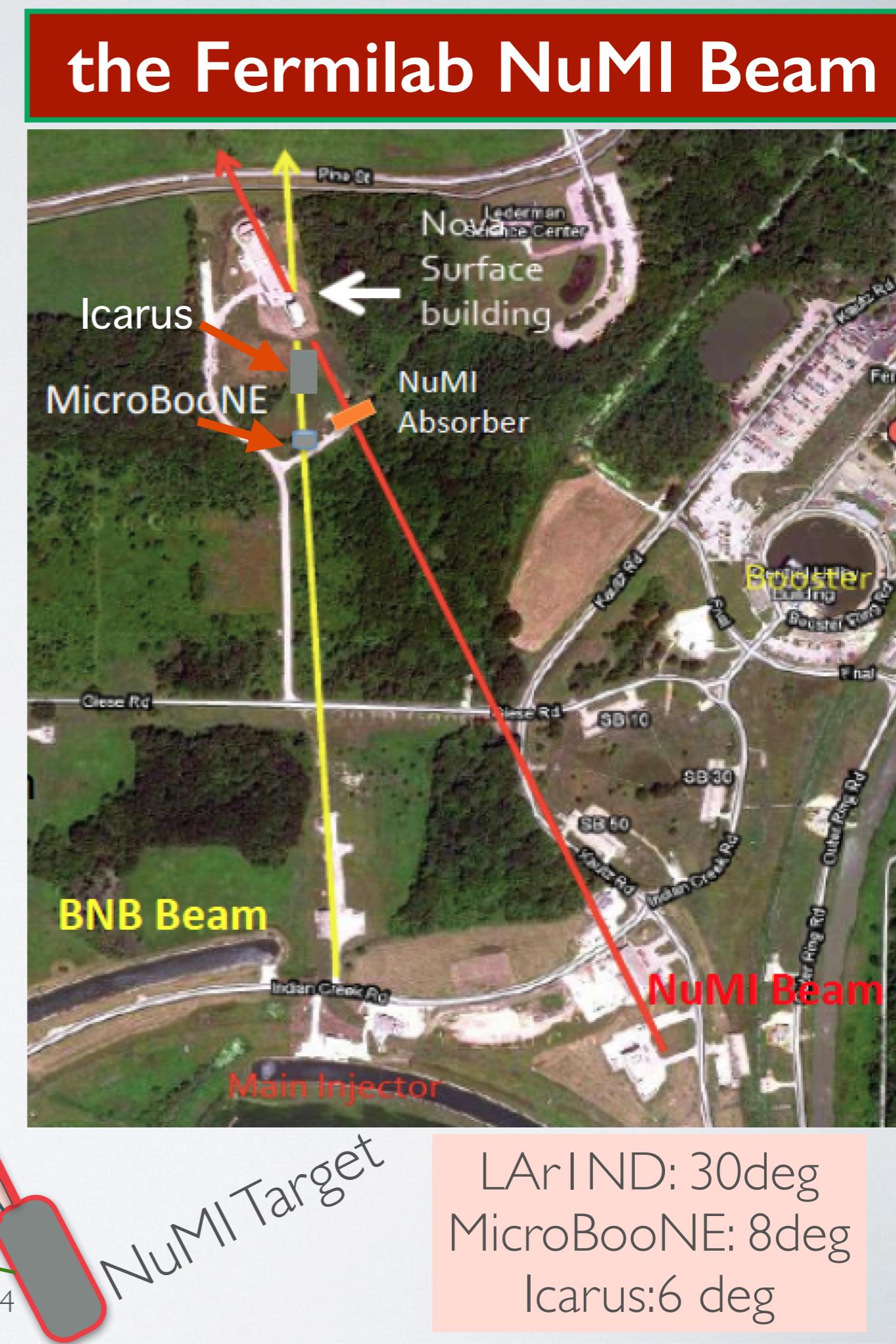
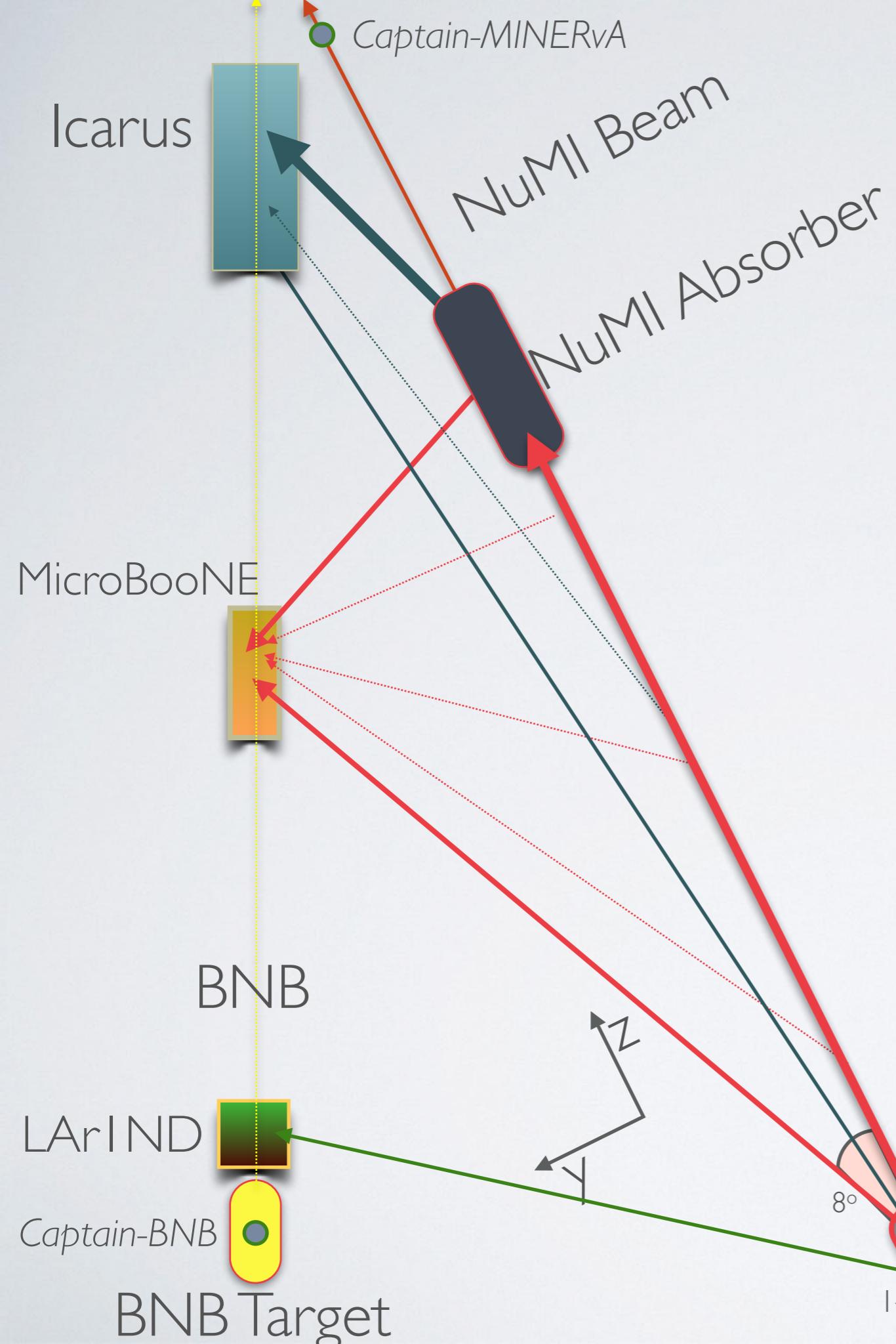
Rates: 2e20 POT (1 yr) & 100% efficiency

$\nu_\mu$ (NC): +14%,  $\bar{\nu}_\mu$ (NC): +31%

These locations are outside the  
MI-12 building

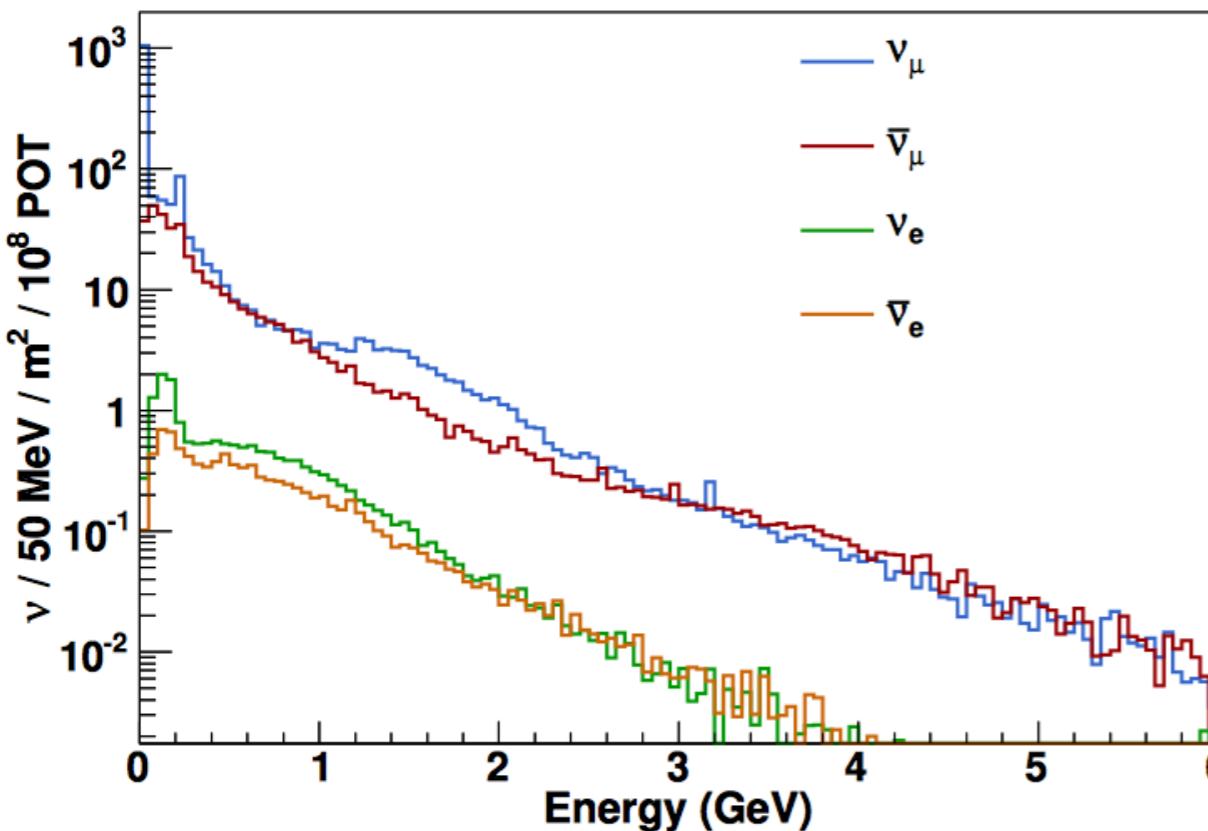


All 6 locations shown are on the ground level, 8.4 m above the target level (position A is directly above the target)

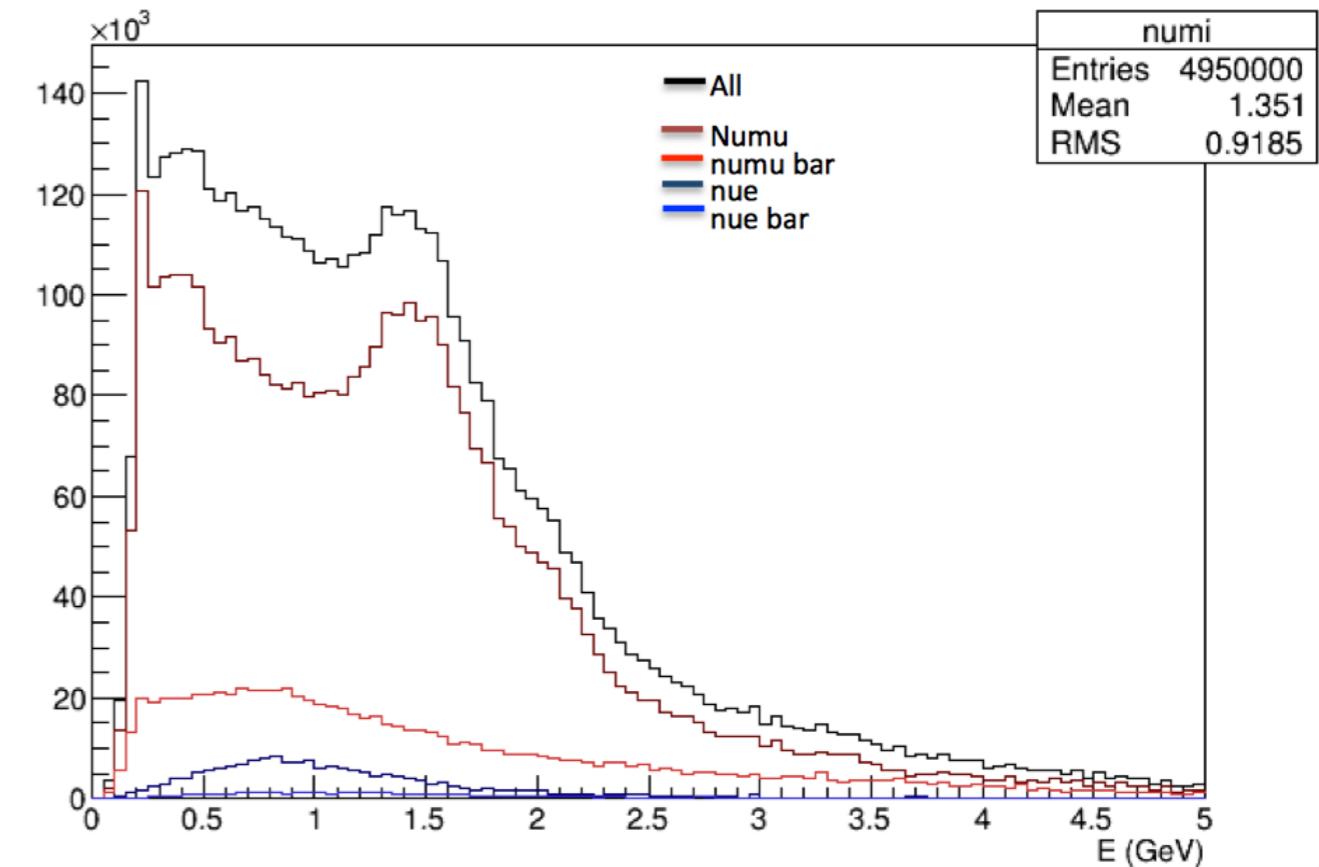


LArIND: 30deg  
 MicroBooNE: 8deg  
 Icarus: 6 deg

### NuMI flux at MicroBooNE



### Event from numi in nu mode at 470m



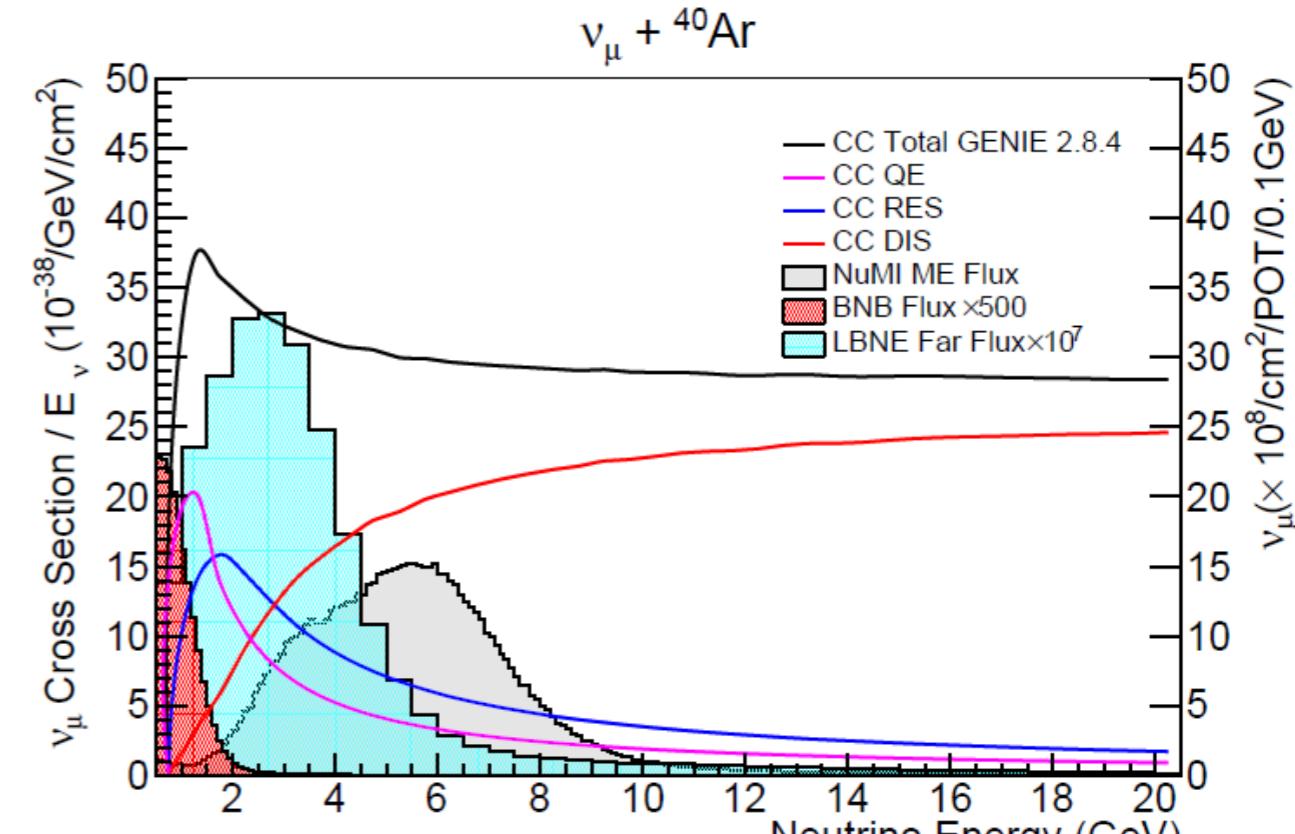
|             | $\nu$ | $\nu$       | $\nu_{\text{ABS}}$ |
|-------------|-------|-------------|--------------------|
| LArIND      | 15 k  | 0.7 k       | 20                 |
| MicroBooNE  | 60 k  | 3 k         | 30                 |
| Icarus T600 | 600 k | <b>30 k</b> | 100                |

$3 \times 10^{20} \text{ pot/yr} \times 3 \text{ yr}$   
in detector Active Volume

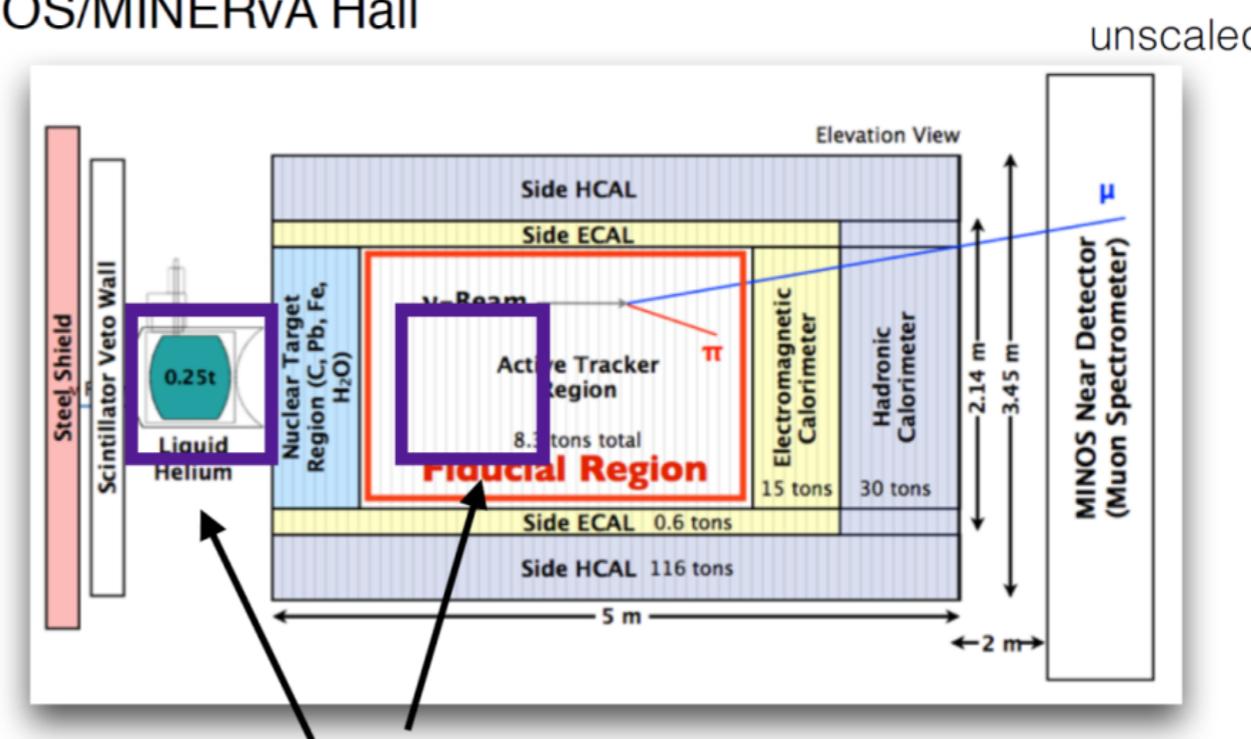
A large fraction of the rate is  
**below 0.5 GeV** and  
**above 1.5 GeV**  
(complementary to BNB).

## NuMI Beam: MINOS-ND/MINERvA Hall

- ▶ Install the CAPTAIN detector in MINERvA to study neutrino-argon interactions in the medium-energy NuMI beam
- ▶ Expands the physics reach of both experiments in a way that is complementary to existing LAr R&D
- ▶ Only experiment making high-statistics measurements of neutrino interactions on argon in the medium energy range before ELBNF
- ▶ CAPTAIN-MINERvA can measure cross section ratios (i.e. argon to carbon)
  - ▶ Study how processes vary on different nuclei
  - ▶ More stringent tests of the models can be performed with ratios due to cancellation of large systematic uncertainties such as the neutrino flux
- ▶ More statistics and better containment than achieved with ArgoNEUT
- ▶ In an energy range complementary to MicroBooNE
  - ▶ Covers 1<sup>st</sup> oscillation max for oscillations at a baseline of 1300 km
  - ▶ Majority of interactions are DIS or resonance rather than CCQE



MINOS/MINERvA Hall



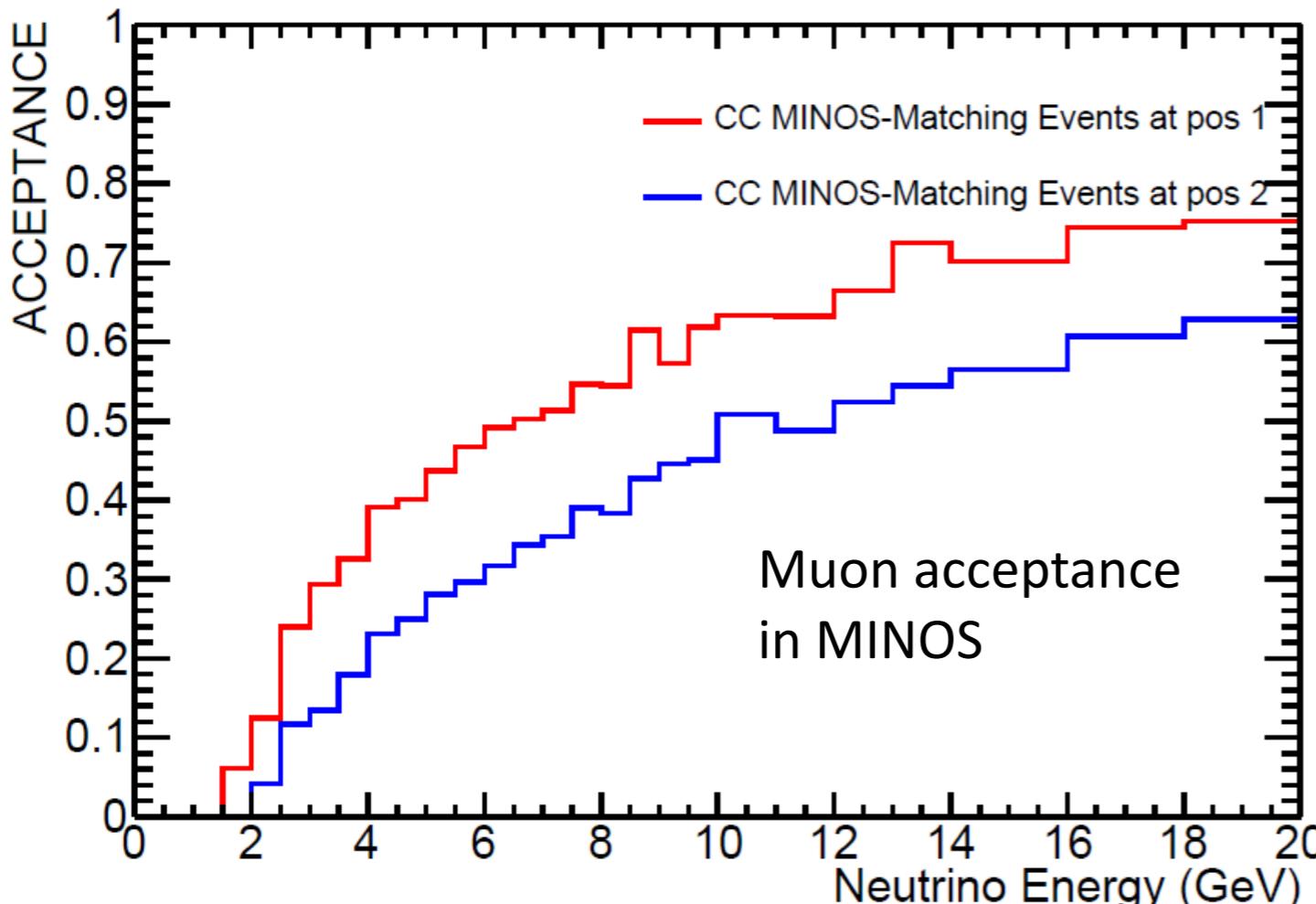
Two possible locations

- at the position of the He target
- at the module 30 (removing half of the tracker)

CCQE-like =  
muon + any  
number  
protons and no  
pions

|                 | Contained<br>Events in<br>CAPTAIN | Contained Events<br>in CAPTAIN at pos 1<br>w/MINOS Match | Contained Events<br>in CAPTAIN at pos 2<br>w/MINOS Match |
|-----------------|-----------------------------------|--|--|
| CC 0 $\pi$      | 488,250                           | 255,354  | 339,333  |
| CC1 $\pi^{\pm}$ | 191,250                           | 59,478   | 88,930   |
| CC1 $\pi^0$     | 189,000                           | 48,384   | 76,167   |

Table 1: Contained efficiency for CC events with a reconstructed muon using MINOS ND, assuming  $6 \times 10^{20}$  POT exposure.



Contained events: events in which all outgoing particles except neutrons and leptons are contained within CAPTAIN; overall containment efficiency is 25%.

Neutrino energy threshold of 1.5-2 GeV for CC events with a muon matched in MINOS.

In the search for sterile neutrinos with a mass of  $\sim 1\text{eV}$  (at BNB), there are uncertainties in *neutrino flux*, **cross sections**, **incident neutrino energy assignments**, oscillation parameters and **detector response**.

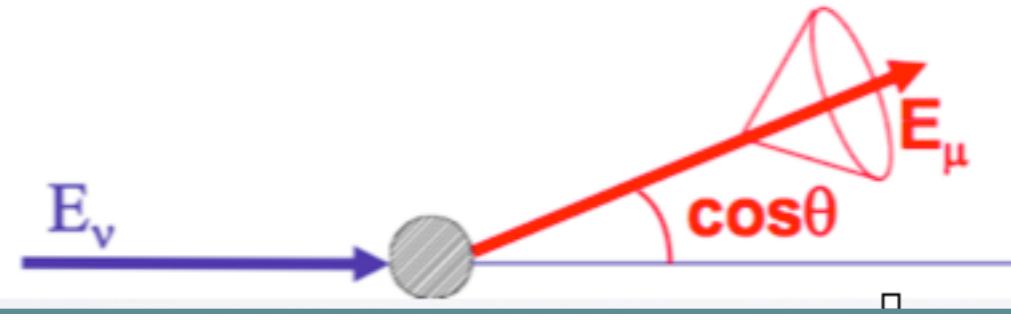
Statistics at BNB is very large, in particular in LArIND. This allows for extremely precise **Exclusive XSECT measurements - *including rare processes***.

Are there other measurements that enhance what can be learned about neutrino interactions from the FNAL (SBL) LAr program?

**Incident neutrino energy assignments**  
**ArgoNeuT → MicroBooNE (and beyond)**

**Detector Response**  
**LArIAT**

# Neutrino energy reconstruction



$$1) \quad E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos \theta_\mu)}$$

MUON ONLY

$$p_h = \sqrt{(E_\nu - p_\mu \cos \theta_\mu)^2 + p_\mu^2 \sin^2 \theta_\mu}$$

$$\cos \theta_h = (E_\nu - p_\mu \cos \theta_\mu) / p_h$$

**predicted proton angle  
and momentum**

assumes QE events!  
and interaction on a  
nucleon at REST

$$2) \quad E_\nu = p_\mu \cos \theta_\mu + p_p \cos \theta_p$$

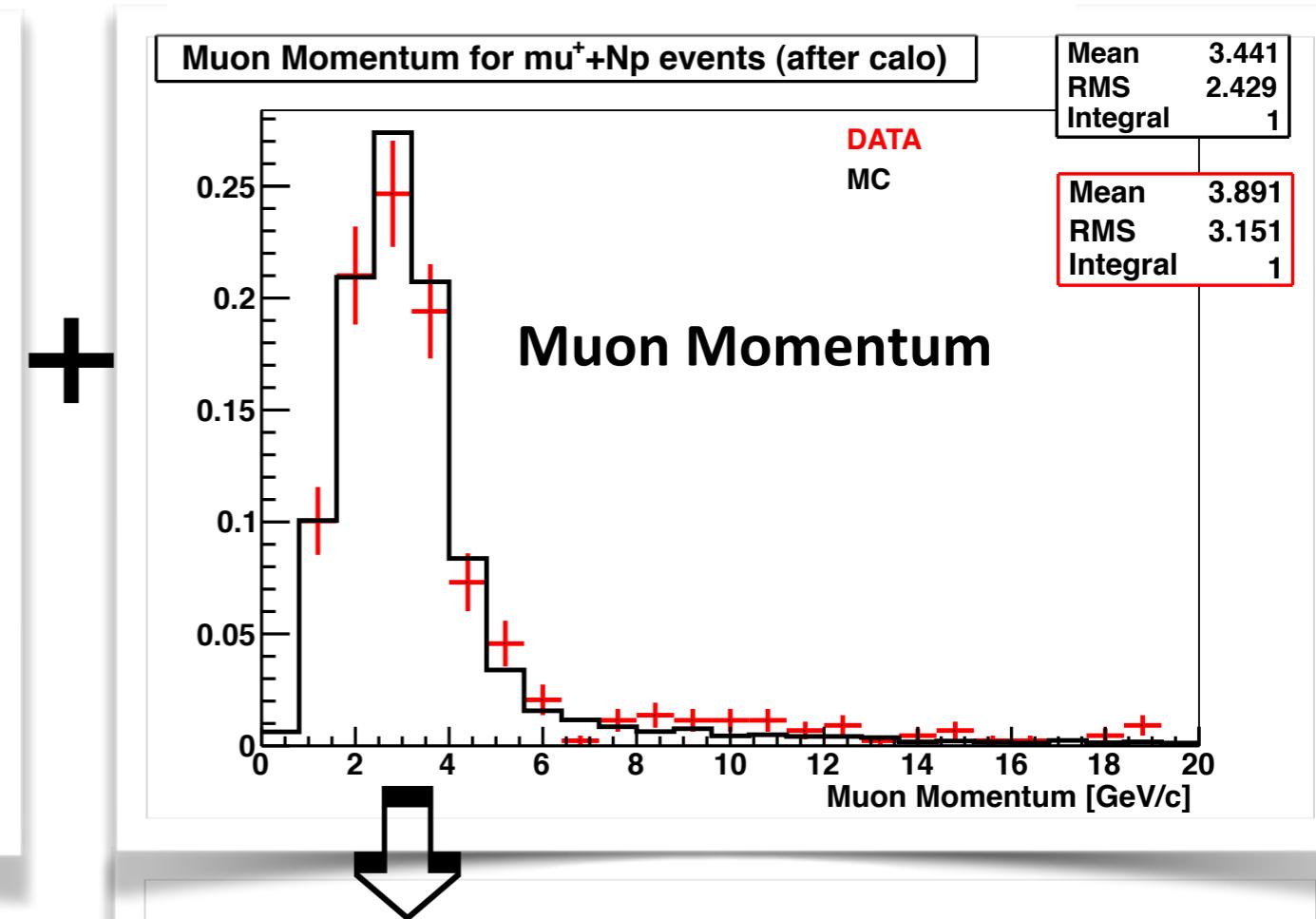
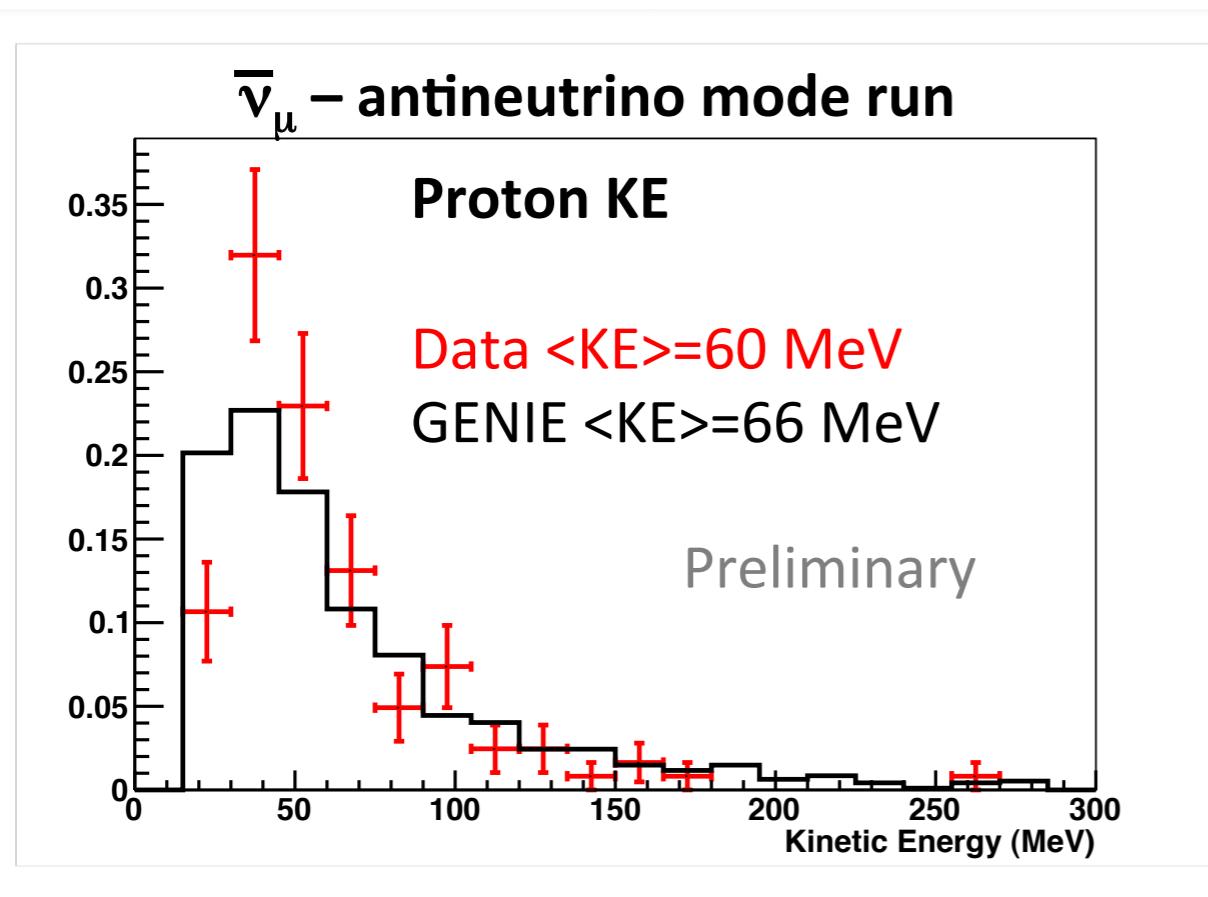
$\mu + p$  kinematics  
( $p_p$  and  $\theta_p$ )

$$3) \quad E_\nu = E_\mu + \sum T_{pi}$$

**ENERGY CONSERVATION**

$\mu + p$  kinematics  
( $p_p$  and  $\theta_p$ )

# Neutrino energy reconstruction in ArgoNeuT - AntiNeutrino CC $0\pi$ sample ( $\mu^+ + Np$ )

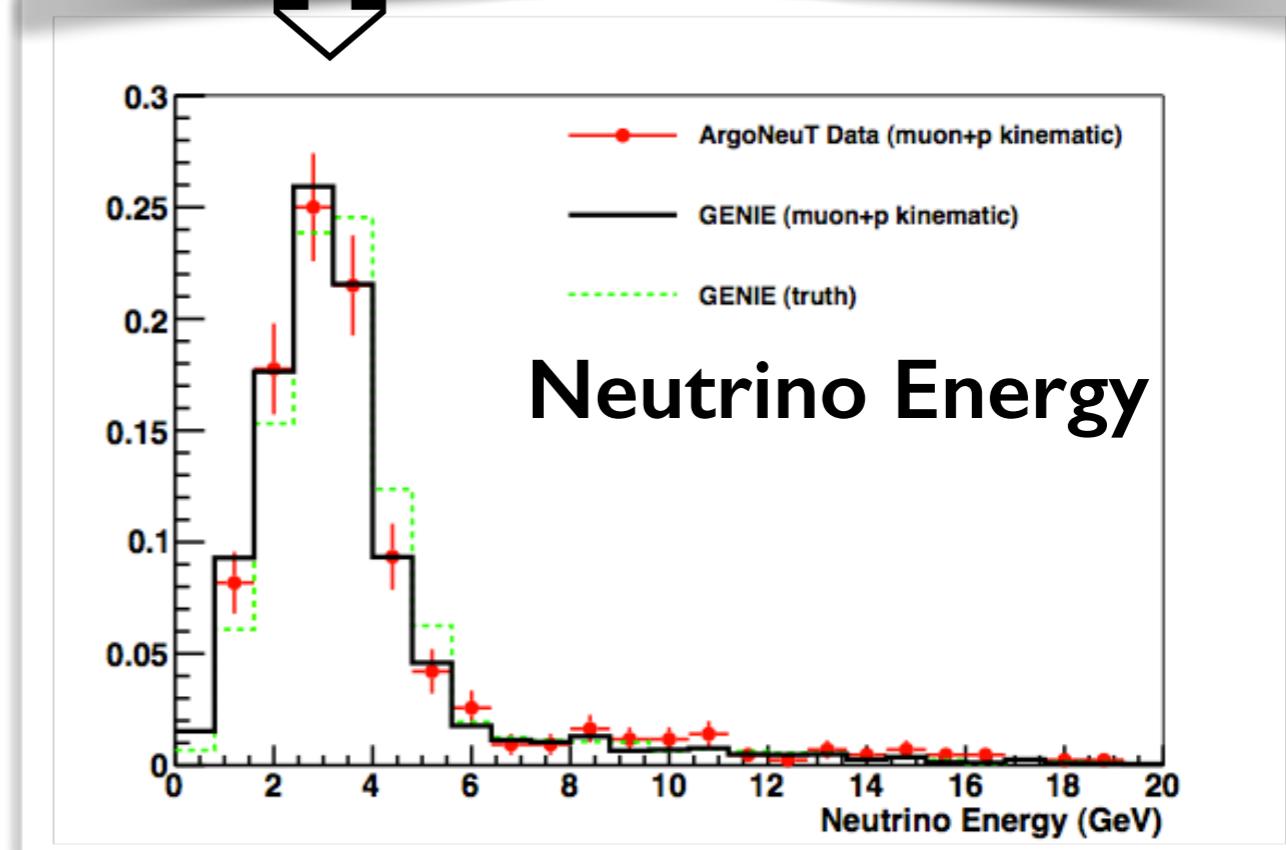


Neutrino Energy from muon + protons  
reconstructed kinematics:

$$E_\nu = E_\mu + \sum T_{pi}$$

No just muon information

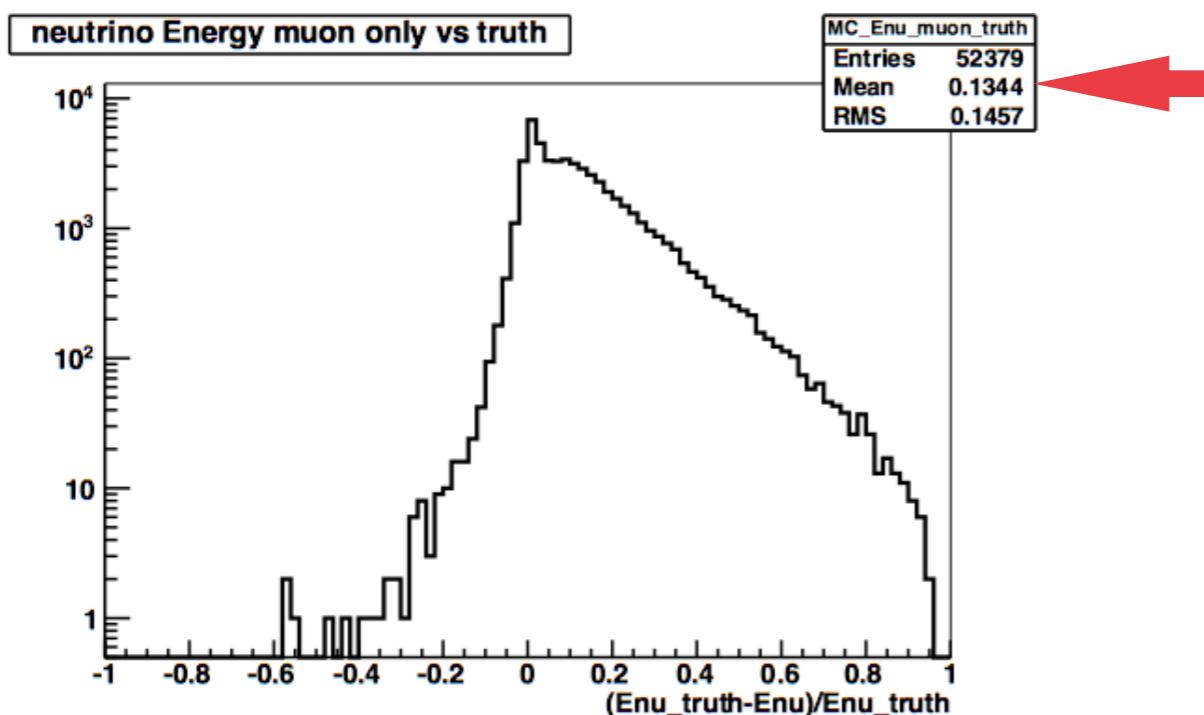
Reconstruction of other kinematic  
quantity ( $q$ ,  $Q^2$ ,  $p_{miss}^T$  etc.)



# GENIE MC

$\bar{\nu}_\mu$  CC 0-pion  
 $(\mu^+ + Np)$

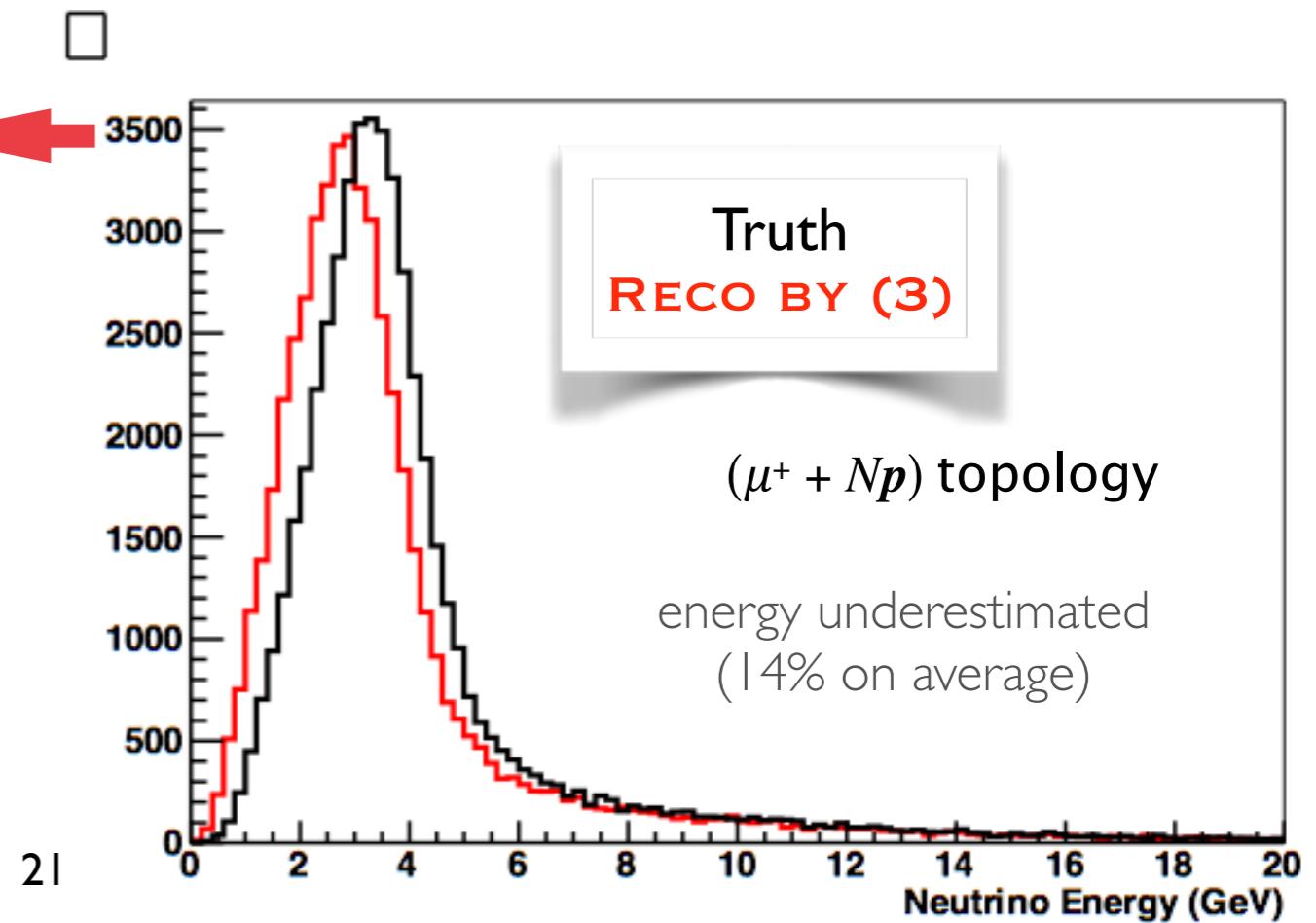
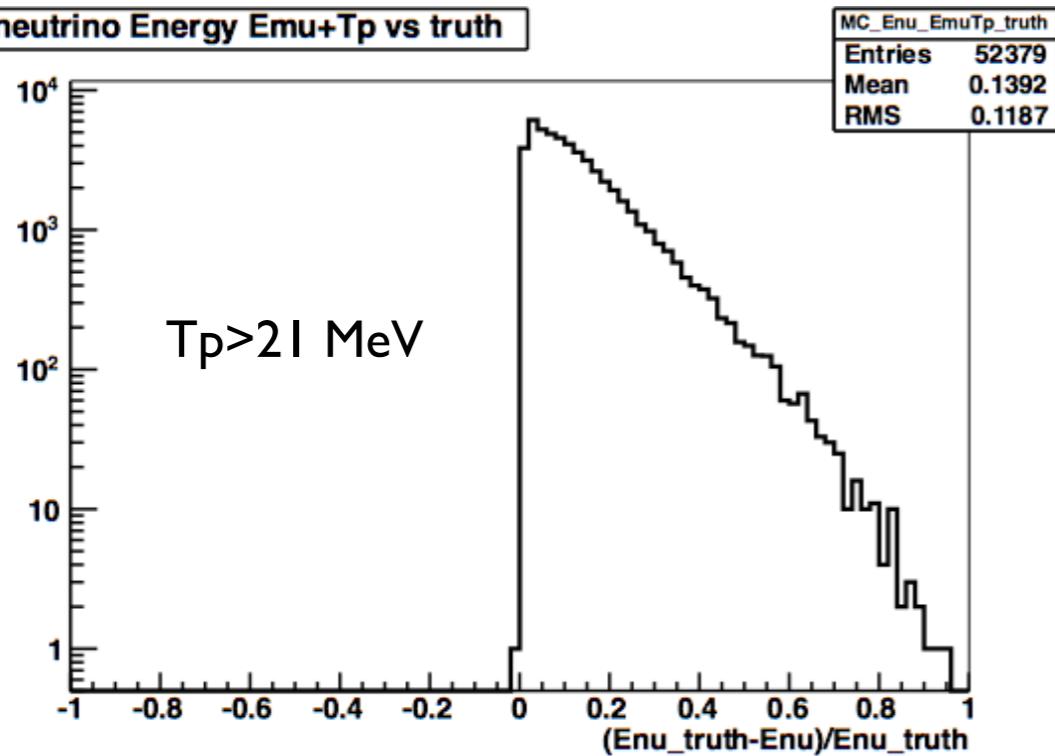
## 1) MUON ONLY



Energy reconstruction:

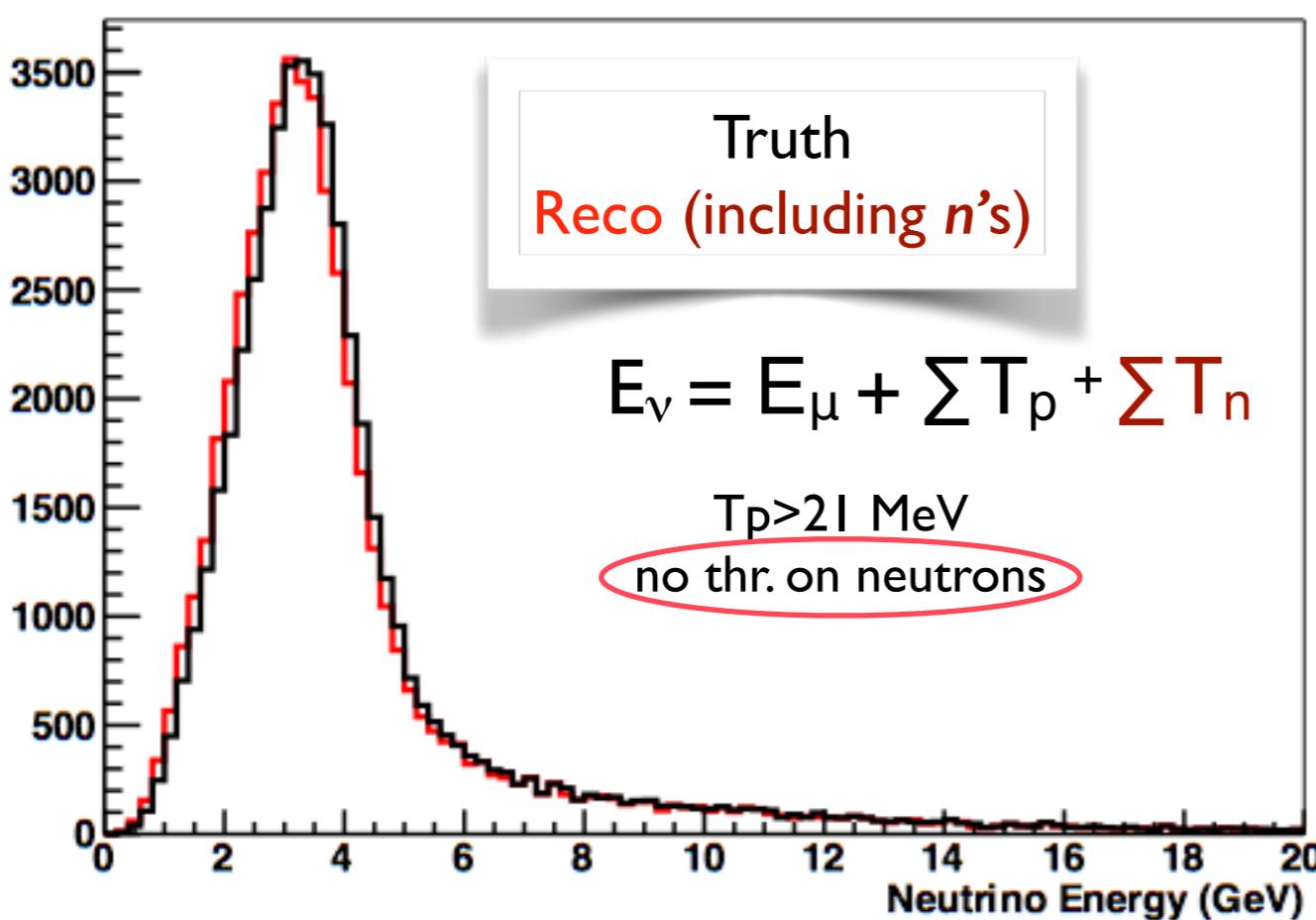
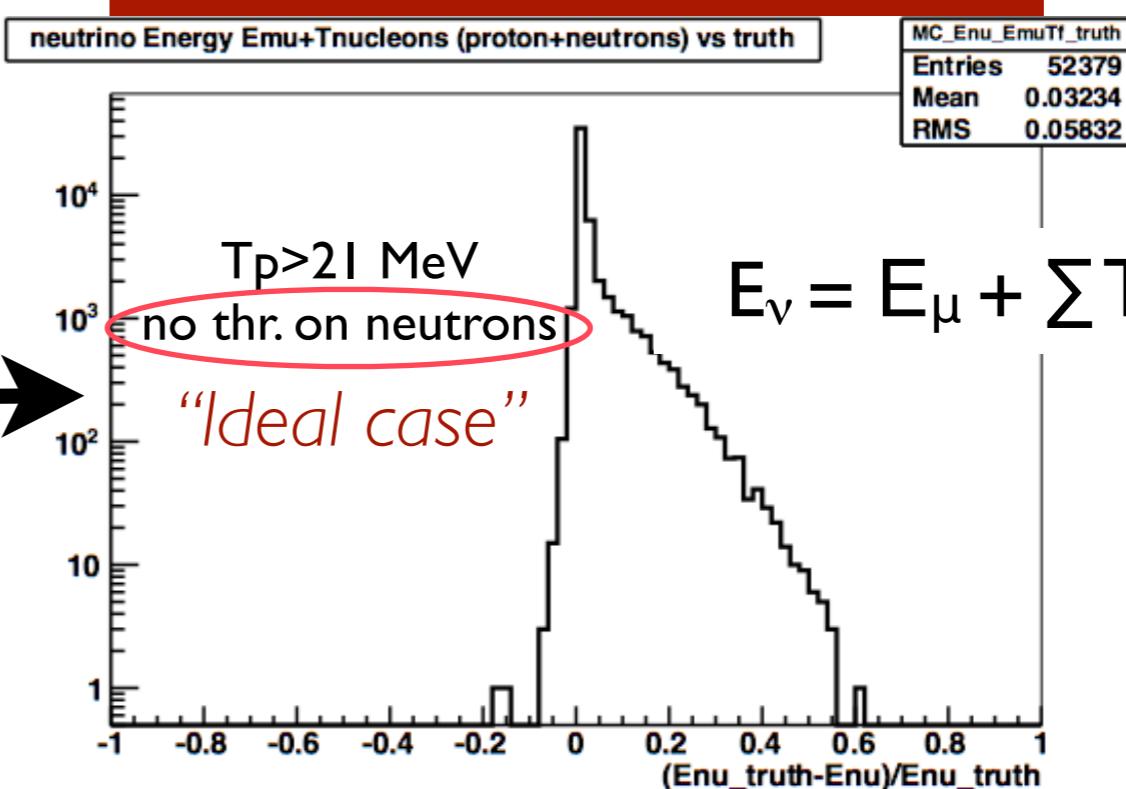
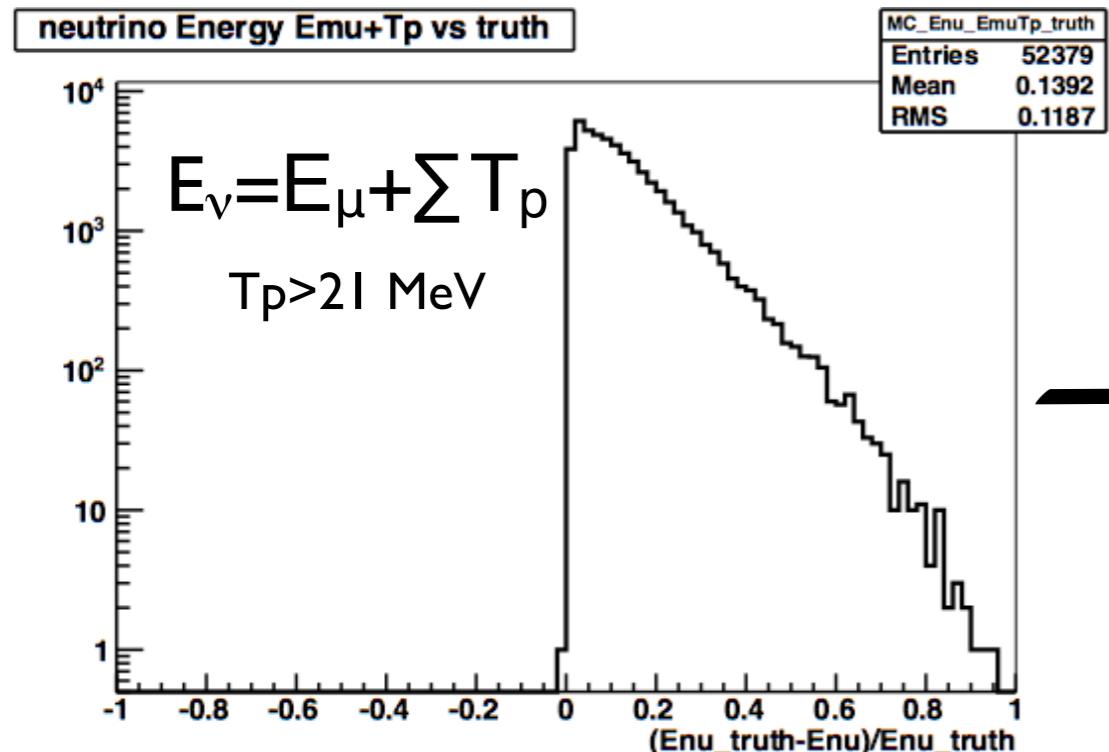
$$\frac{E_\nu^{\text{truth}} - E_\nu^{\text{reco}}}{E_\nu^{\text{truth}}}$$

## neutrino Energy Emu+Tp vs truth



## 3) ENERGY CONSERVATION

# Including neutrons...

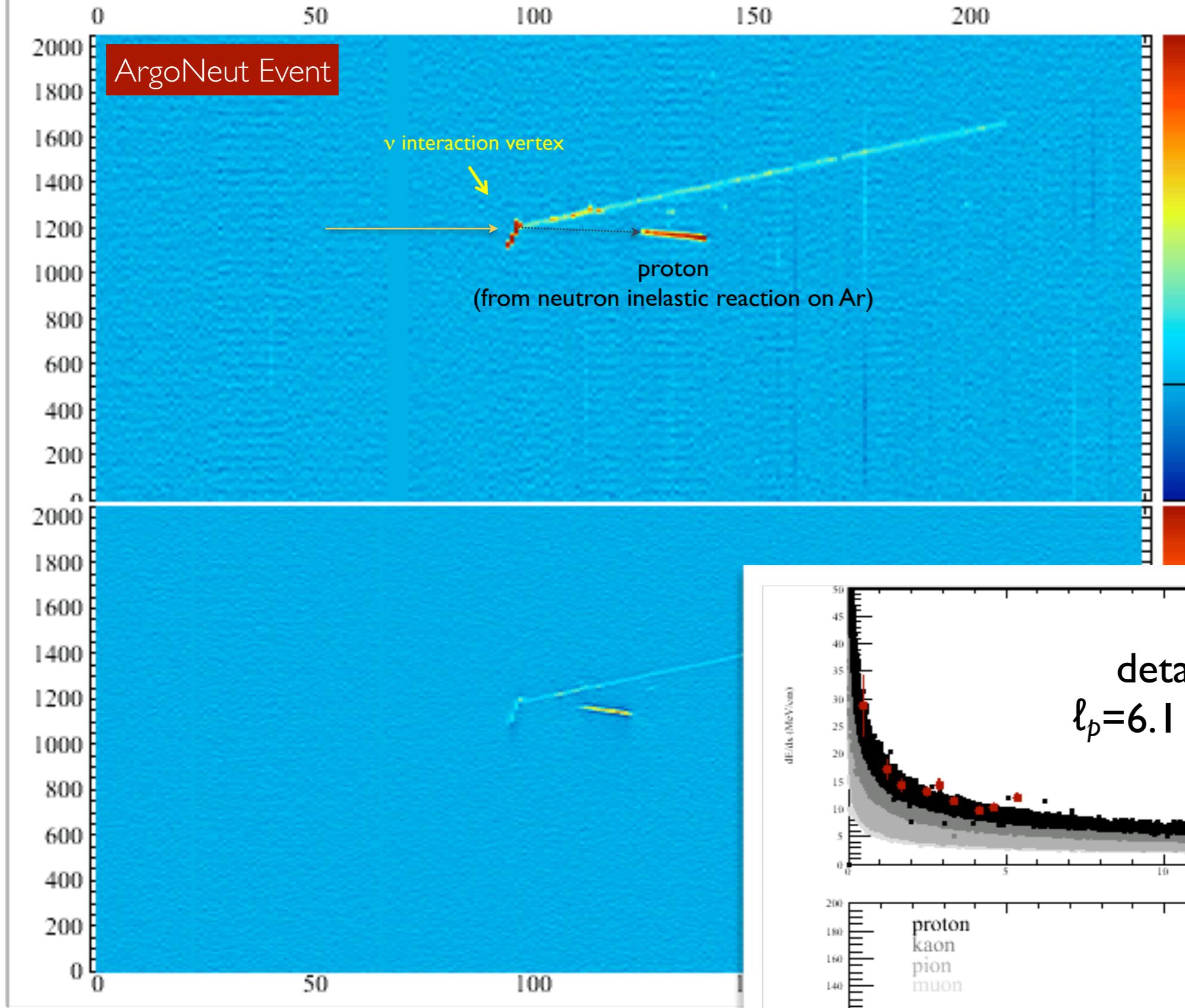


# GENIE

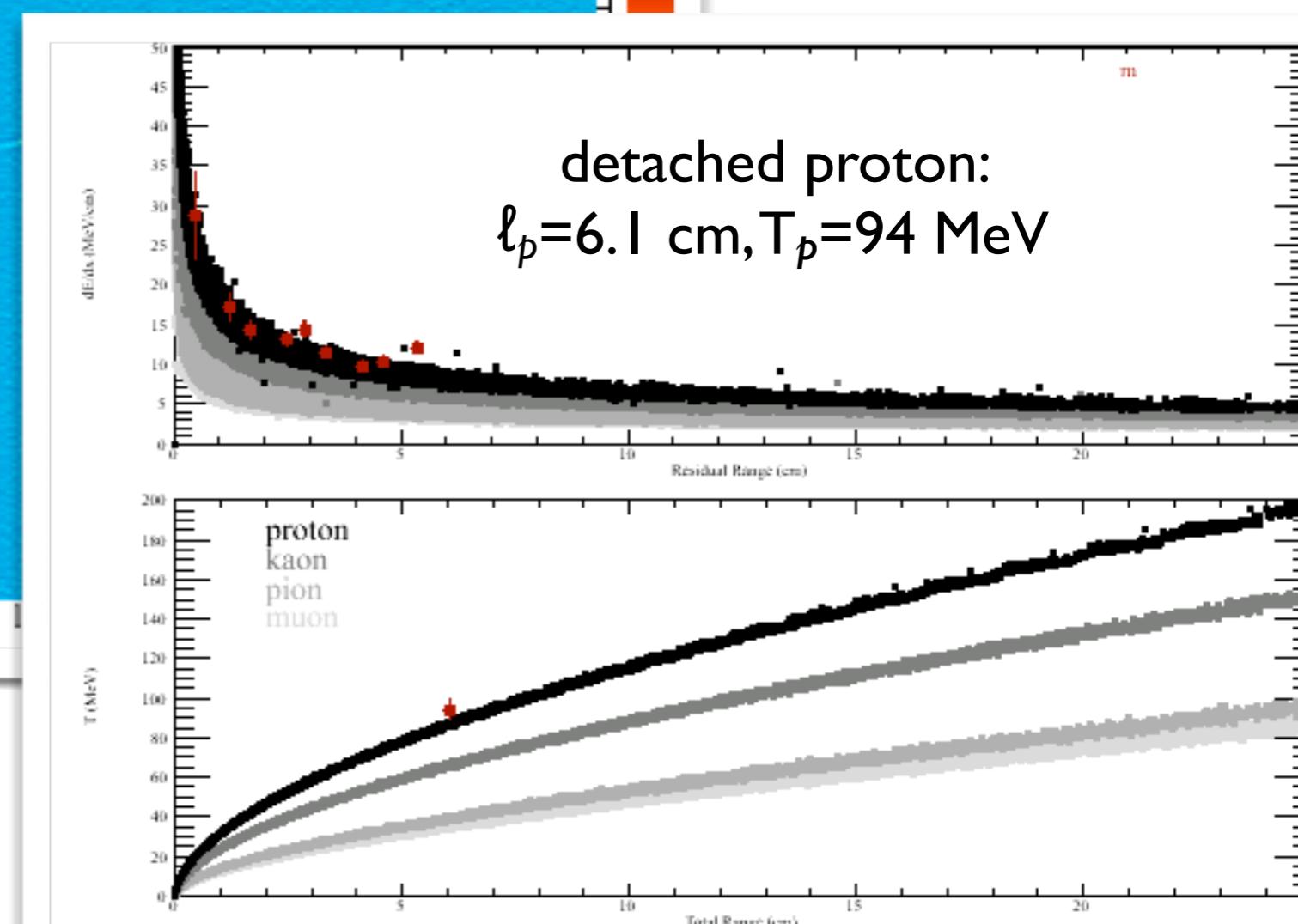
$(\mu^+ + Np + Kn)$  topology

Important to reconstruct also neutrons, in particular at low energy (MicroBooNE)!

NB: residual difference mainly due to **Missing Energy** ( $E_{\text{miss}} = E_{\text{sep}} + \epsilon^*$ ) depends on  $N$  and  $K$  (*can be estimated*)



*Reconstruction  
of proton(s)  
from neutron  
inelastic  
reaction on Ar*

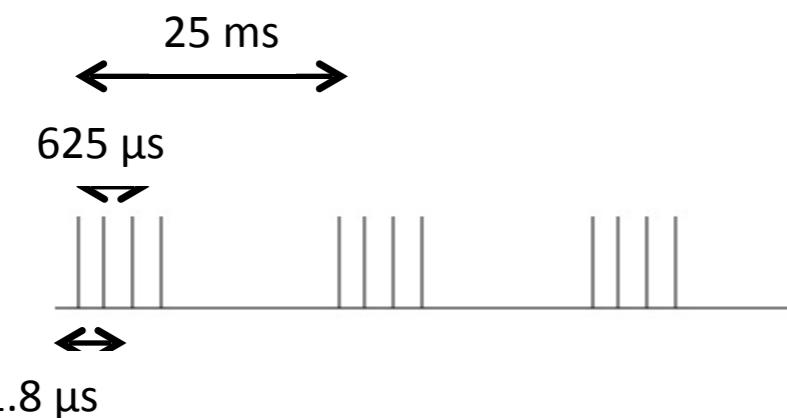


Only few events with  $n \rightarrow p$  in  
ArgoNeut

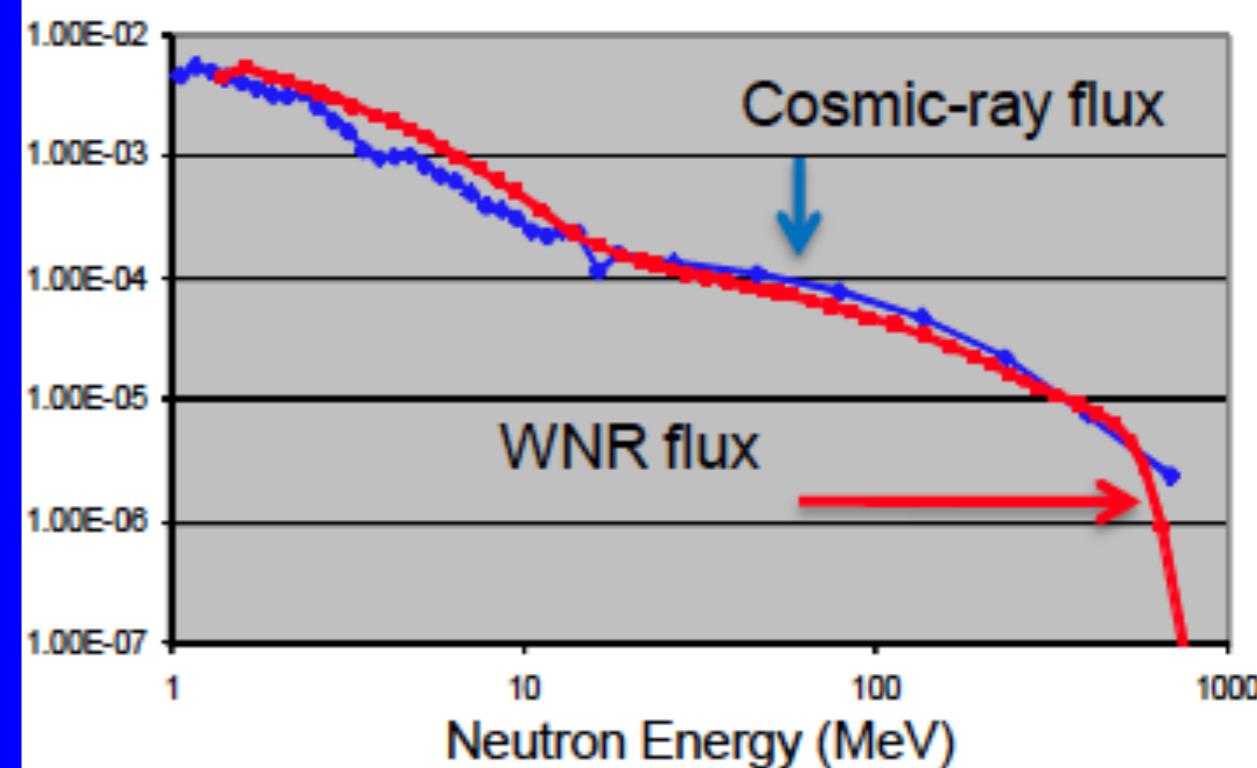
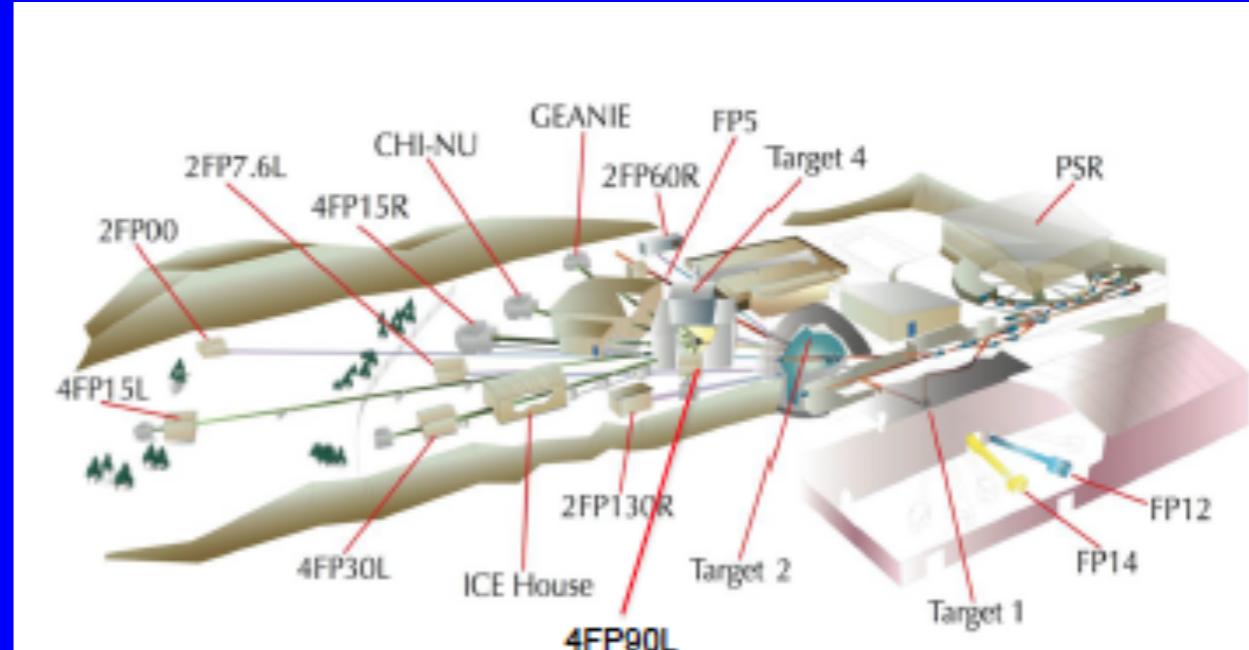
LAr volume dimensions  $\leq \lambda_{int}$

# CAPTAIN on the Neutron Beam at LANL

- Los Alamos Neutron Science Center WNR facility provides a high flux neutron beam with a broad energy spectrum similar to the cosmic-ray spectrum at high altitude



- Time structure of the beam
  - sub-nanosecond micro pulses 1.8 microseconds apart within a 625  $\mu$ s long macro pulse
  - Repetition rate: 40 Hz

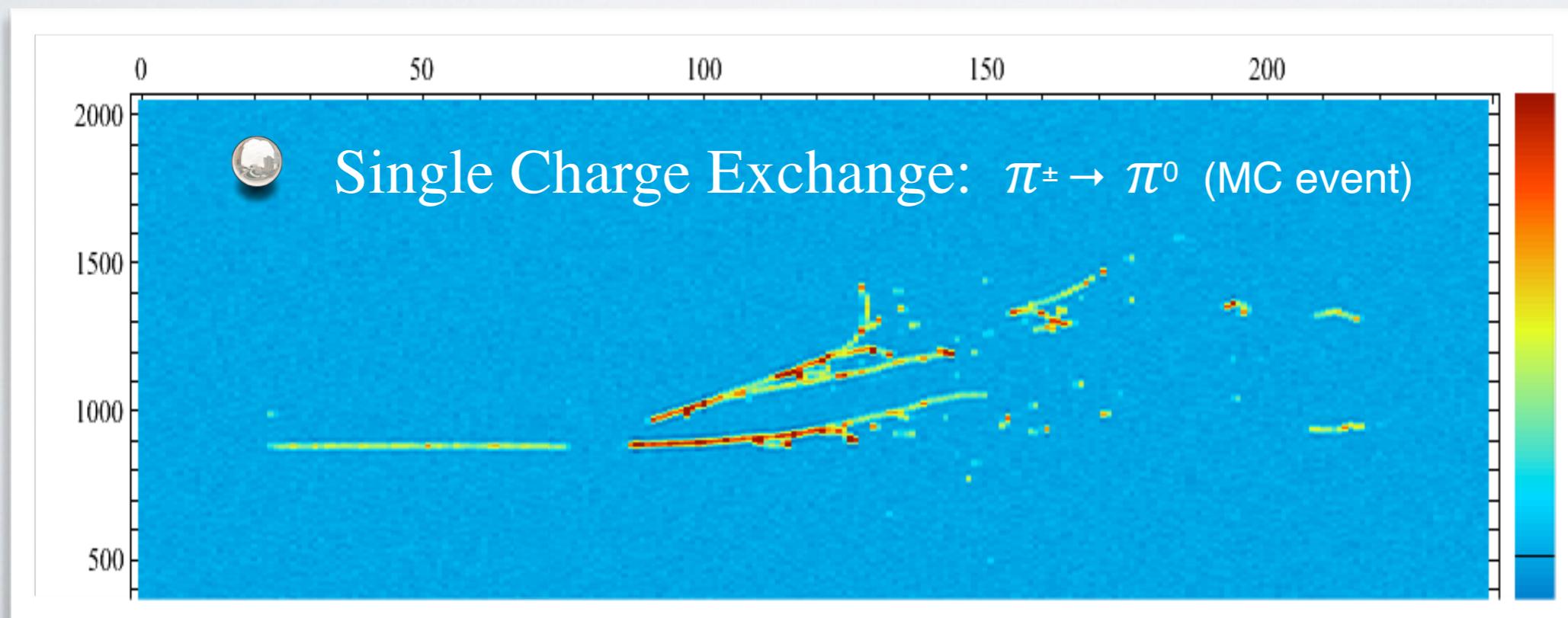


Improvement in detector response (*PId, Calorimetry, Charge separation*) requires dedicated effort (sw& hw) but also **direct physics measurements**:

**LARIAT AT FTBF** (starting now) and future test beam efforts at CERN

## One example:

direct measurement of the **Pion ChEx Cross Section on Ar (single Charge Exchange process)** never measured, a value with large error is now assumed as extrapolated from pion reactions on Carbon)



In conclusion:

- Highest resolution & XLarge Statistics LArTPC Data *in the few hundred MeV to few GeV energy range, using the Booster & the NuMI beams* are expected from the “present” and “Intermediate” LAr neutrino program at FNAL  
**(MicroBooNE and SBN-Trio and Captain-SBN/Captain-Minerva, respectively )**

- prominent Goals:

- reliable reconstruction of the incident neutrino Energy
- explore nuclear effects (e.g. nucleon-nucleon correlations in Nuclei) importing methodology and competence from electron-scattering
- discriminate among theoretical models
- develop/tune MC generators.

### Important ingredients:

- Detection of emitted neutrons (*from inelastic interaction(s) on Ar nuclei*)
- proton multiplicity (and their angular correlations) at the interaction vertex
- (*MC independent*) Exclusive Cross Section measurements at high statistics
- first detection of  $\nu_e$  - Ar ABSorption reaction, relevant for SN detection
- Test Beam Study of Charged & Neutral Particle interaction processes in Ar (*in the energy range relevant for SBN & LBN*)

BackUp Slides

# Example of Low energy proton reconstruction



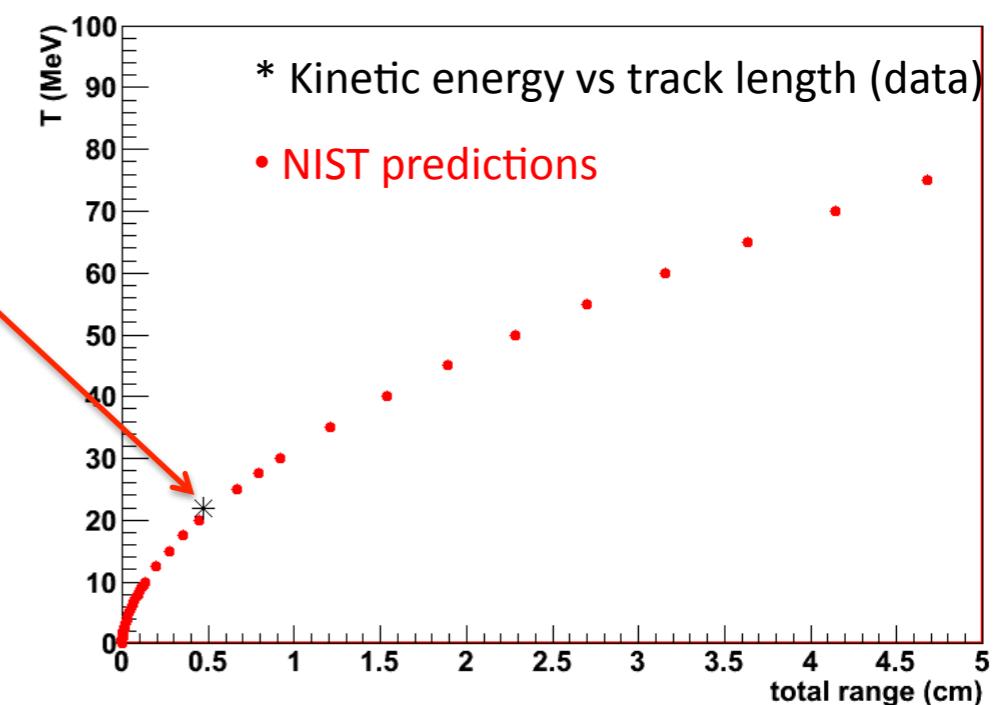
The short track behaves like proton



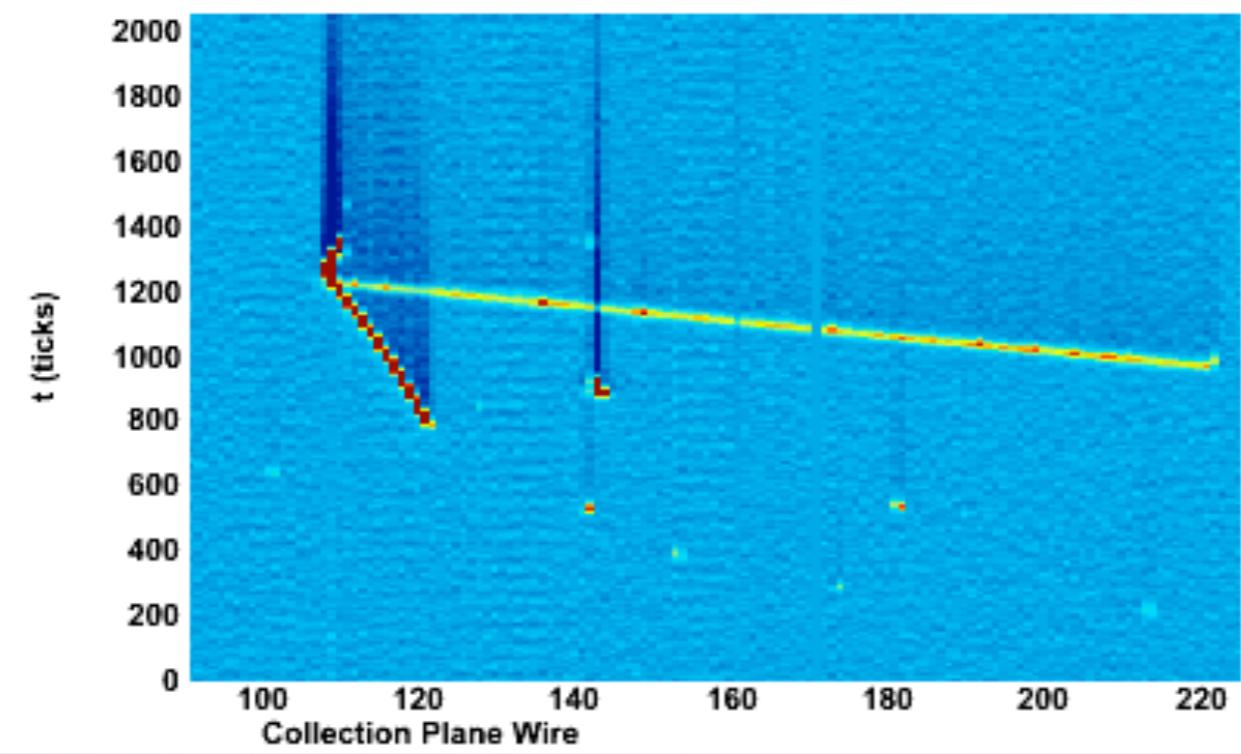
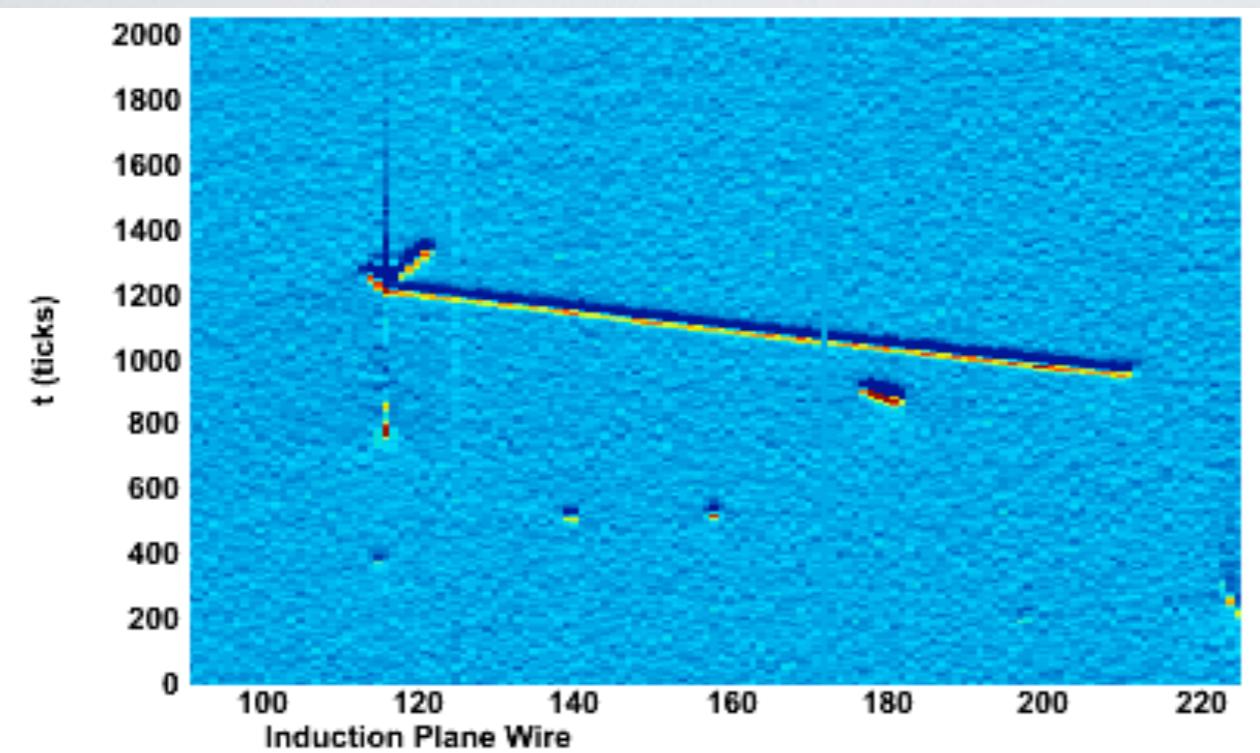
The event is (CCQE)  $1p - 1\mu^-$

Length=0.5 cm

$KE = 22 \pm 3$  MeV



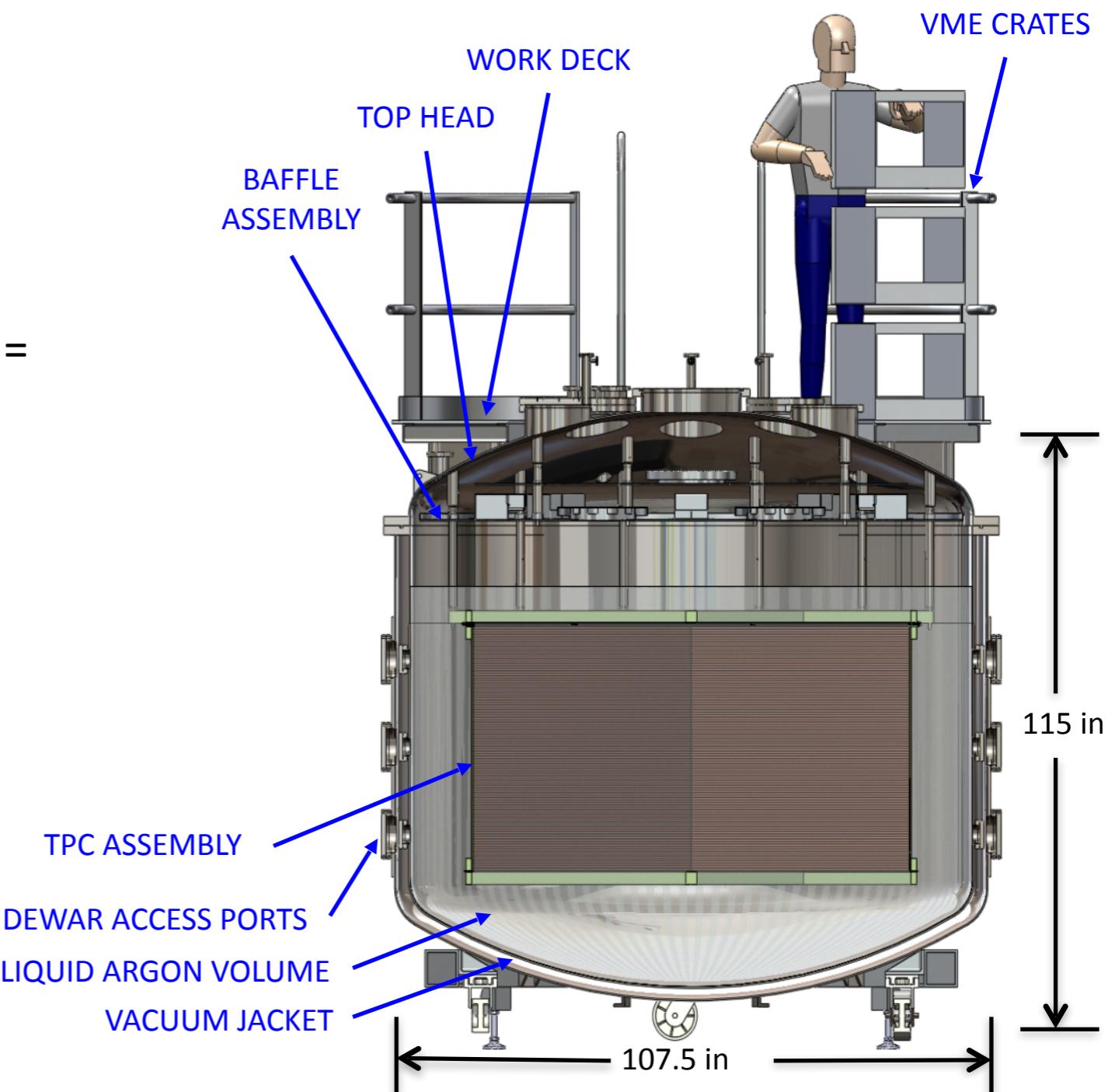
ArgoNeuT proton threshold: 21 MeV of Kinetic Energy



# CAPTAIN

Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos (LANL LDRD)

- Liquid argon TPC detector:
  - Portable and evacuable cryostat
  - 5-ton instrumented liquid argon
- TPC:
  - Hexagonal prism, vertical upward drift ( $E = 500 \text{ V/cm}$ ,  $v_d = 1.6 \text{ mm}/\mu\text{s}$ )
  - 2001 channels (667/plane)
  - 3 mm pitch and wire spacing
- Laser calibration system (Nd-YAG)
- Photon detection system
  - Hamamatsu R8520 (24) & 11065 (4)
- $\mu$ BooNE cold electronics
- Mini-CAPTAIN: a smaller prototype detector



# $(\mu + 2p) - \nu$ energy reconstruction

From all final state particles kinematics

$$E_\nu = E_\mu + (T_{p1} + T_{p2}) + T_{A-2} + E_{miss}$$

We have no access to the longitudinal component of the missing momentum  
we may lower bound

$$T_{(A-2)} \leq \frac{(P_{miss}^T)^2}{2 M_{A-2}}$$

$$E_{miss} = E_{sep} + \epsilon^*$$

$E_{miss}$ =energy expended to remove  
the nucleon pair from the nucleus.

$E_{sep}$ =two-nucleon separation  
energy for argon

$$E_{sep} = M_{(A-2)} + 2m_p - M_A$$

$\epsilon^*$ =actual excitation level of the  
residual nucleus

We set the total value to a constant  $E_{miss} = 30$  MeV. This is an approximation of the average  
energy to remove an np pair from an Ar nucleus extrapolated from single nucleon removal  
energy spectra for Ar nuclei.

trino energy for the  $(\mu^-)$   
 $(E_\mu + T_{p1} + T_{p2} + T_{A-2})$   
inferred from the final state  
inferred from the final state  
tons) measured kinematic  
corrections: the residual  
however a lower bound  
be calculated using the n  
momentum as  $T_{A-2} \approx (P_{miss}^T)^2 / (2 M_{A-2})$   
includes two terms, nam  
energy for argon [16] an  
the residual nucleus. We  
 $E_{miss}=30$  MeV. This is a  
energy to remove a np p  
lated from single nucleon  
nuclei [17].